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DEGREE FOR WHICH THESIS WAS PRESENTED Master of Science

YEAR THIS DEGREE GRANTED Spring 1980

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The Physical Geography of the Rabbitkettle Hot Springs, Nahanni National Park, N.W.T.

by

©
David J. Wright

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF Master of Science

Department of Geography

EDMONTON, ALBERTA

Spring 1980

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled The Physical Geography of the Rabbitkettle Hot Springs, Nahanni National Park, N.W.T. submitted by David J. Wright in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

Three large tufaceous mounds are situated in the northwestern corner of Nahanni National Park, N.W.T., in the area known as Rabbitkettle. These mounds build up from the precipitation of calcium carbonate of the highly mineralized waters discharging from hot springs. A north mound is isolated from the others and stands 14.7 m above a terrace feature. The two southerly mounds are at a similar height but have fused together to form one feature.

This study examines the physical geography of the hot springs and their immediate area. Physical geography includes a description of bedrock geology and geomorphological processes within the region, origin of the hot spring mounds and the various physical and chemical aspects of the mounds.

The temperatures of the waters were almost constant throughout the field season, being 21.5^{0}C for Mound 1, 21^{0}C for Mound 2 and 20.6^{0}C for Mound 3. Discharge increased from 0.03 cumecs for Mound 1 to 0.07 cumecs towards the end of the field season (August); a rise from 0.01 to 0.03 cumecs was recorded for Mound 2. Hardness of the waters was also measured and remained fairly constant - 529 ppm total hardness for Mound 1, 507 ppm for Mound 2 and 502 ppm for Mound 3.

Other geochemical tests showed that only a very small part of the waters (less than 25 ppm) consisted of Na, K, Fe, Mn, Cu, Pb, Zn, SO_4, Cl, F and SiO_4. Isotopic analyses

of the waters showed that they are similar to environmental water and therefore are meteoric. Chemical analyses by X-ray diffraction showed that the tufa is very pure, greater than 99.5 percent $CaCO_3$. A chemical precipitate associated with snowbanks was also discovered.

Physiographic analysis showed that there is a relationship between rimstone pool width and slope of mound; a linear relationship between rim height and pool width and a linear relationship between thickness of tufa and slope of tufa rim.

Periglacial activity is present upon the mounds themselves and may play an important part in the breakdown of the tufa. Features such as patterned ground, frost heave mounds and spalling are all present.

Algal growth in the main outflow of the three mounds aids the precipitation of tufa on the mounds. On the third mound, unusual calcified vegetational hillocks or mounds, about 10 cm high and 15 cm in diameter have formed. Two distinguishable forms of these mounds have been identified. Moss is the main base upon which the calcium carbonate precipitates and then provides an organic base for higher plants to colonize. The process of colonization of these vegetational mounds is examined. Colonization by higher plants such as gymnosperms give an insight into the rate of deposition of the tufa.

Dating of the mounds is estimated by their superposition upon the terrace feature, and by tree growth

within the calcified vegetational mounds. By these methods the rate of deposition was determined as between 2.5 mm/1000 years and 2.7 mm/1000 years.

ACKNOWLEDGMENTS

I would like to acknowledge the great number of people who have made contributions to the scientific and social facets of my thesis over the past couple of years. In particular, I would like to thank my supervisor, Dr. Michael C. Brown, who not only acted as my supervisor but was also a great friend during my two years at the University of Alberta.

A special thanks also goes to the other two members of my committee, Dr. Bruce Rains and Dr. Peter Thompson, who spent long hours reading and evaluating this thesis. For this I express my utmost appreciation.

I was fortunate to have a field assistant of the calibre of Madeline McKeever whose knowledge of botany proved to be an immense help to this thesis. I would like to thank her very much for the great help for those two months at Rabbitkettle.

I would like to thank Kim Davis for his cartographic services and the magnificent work he did on the maps. Gerald Stark and Stephanie Kucharyshyn helped with the drafting of some of the diagrams so a special thanks goes to them.

A special thanks also goes to Ann King who spent long hours editing this thesis and to Linda Hastie who helped type the manuscript into the computer.

At Rabbitkettle, the help from the Parks Canada staff was much appreciated. Therefore thanks go to Eric Hiscock and his wife Vickey; Lou Comin and his wife Cheryl; Phil Burton, Steve Cooper and his wife Muriel; and Chris Hammond

and Marilyn.

Throughout the field season visits from passing scientists and historians were much appreciated. Of these I would like to thank Roly Wickstrom, Bill Addison and Dave Bates.

Scientific analyses were performed by Dr. H. Baadsgard, Dr. P. Thompson and Dr. R. O. van Everdingen. Without their assistance, it would not have been possible to evaluate much of the chemical and physical aspects of the hot springs.

I would also like to thank Sharon Fowler and Marilyn de Wit for their secretarial work and Susan Hogg who did much of the pre-field season arranging of equipment.

Acknowledgments could not finish without thanks to my room mates of 3-9, who showed great ability to remain quiet while I was working. Therefore I send my thanks to Brian Glover, Steve Luck, Olaf Niemann and Ken Thomson for two years of "ideal" working conditions.

Finally I would like to thank Quentin Goodbody for his geological advice and his never-ending stream of compliments while we shared 10736.

INTRODUCTION

The objective of this thesis is an examination of selected geographical aspects of the Rabbitkettle Hot Springs, S. Nahanni National Park, N.W.T., Canada. These include the physical geography of tufa mounds and the particular inter-relationship of these features. The physical geography encompasses the bedrock geology and geomorphology of the area and the springs themselves, biogeography and the physical and chemical aspects of the hot springs; including discharge from the springs, temperature, and water quality.

The Rabbitkettle Hot Springs are situated at $61^{0}57'$N and $127^{0}15'$W; in the northern sector of Nahanni National Park; an irregular strip of land of 4760 square kilometers, straddling part of the Flat River in the southwestern part of the District of Mackenzie, Northwest Territories, Canada (Figures 0:1 and 0:2). The Rabbitkettle Hot Springs are unique in Canada as they are the largest known thermal springs in the country and this uniqueness was the principal reason that Parks Canada extended the newly formed Nahanni National Park (National Parks Act, 7 May 1976), to the junction of the Rabbitkettle and the South Nahanni Rivers. Because of their uniqueness and relatively easy access to the springs from the river, Parks Canada have decided that they must receive adequate interpretation and protection.

Field and Library research was divided into:

1. Bedrock Geology: a knowledge of this is essential to the interpretation of the formation of the hot springs. Much

information was obtained from a report by Gabrielse et al (1965) and from Ford (1974, 76). Field exposures are infrequent so library research was needed to interpret the geology of the region.

2. Geomorphology: mapping the area of the springs and deposits by plane table and by air photograph interpretation was of great use in interpreting the geomorphological history of the springs. Library research into reports by Ford (1974,76) and Marsh and Scotter (1976) was also very useful for this interpretation. Field work was done on the glacial and fluvial deposits surrounding the mounds and on the structures of the mounds themselves. However, the field interpretation of the glacial and fluvial geomorphology is still preliminary.

3. Biogeography: The importance of this was realised only after arrival in the field area. Vegetation and the sequence of its colonization within and surrounding the water vents have a profound effect on the build-up of the tufa. Algae was observed to have colonized the channels used by the spring waters and therefore provide a base for precipitation of $CaCO_3$.

4. Climate: this was measured by Parks Canada over the two month summer period.

5. Physical and Chemical properties

   a. Discharge of water from springs

   b. Temperature of water rising from the springs

c. Chemical aspects including conductivity, pH, dissolved O_2 and CO_2, H_2S, Ca, Sr, Mg, Fe, Mn, Al, Cu, Zn, Pb, Na, K, LI, HCO_3, SO_4, Cl, I, Br, F, PO_4, NO_3, SiO_2, $^{18}O/^{16}O$. (Some of these from van Everdingen, 1973). Sampling intervals for some of the above aspects varied when temporal variations appeared not to exist.

6. Periglacial Activity associated with the Hot Springs: The unique importance of this was not fully realised until after arrival in the field.

Physical Description of the area

The Rabbitkettle Hot Springs are situated about 2 km upstream from the confluence of the Rabbitkettle and Nahanni Rivers on the east bank of the former. They form two distinct mounds, the southerly one being a conglomeration of two mounds formed by water expelling from two separate vents. All these mounds attain a height of 14.6 m above a river terrace and 20.3 m above the Rabbitkettle River (August flow height). Throughout this thesis the mounds are termed: Mound 1, the northerly single-vent mound, and Mounds 2 and 3, the southerly conglomerative mound; Mound 3 being the furthest south (Figure 0:3).

Mound 1, which is the most impressive structurally, stands isolated from the other two in the form of a flat topped hillock (Plate 1). It is the most active of the three and Ford (1974) believes that, assuming the porosity of tufa is 20 percent, the mound contains approximately 530,000 cubic feet or 14,840 cubic metres of precipitated material. Measurements taken in the field reveal that the flat top is 74 m diameter and the circumference at the base is 251 m. The depths of the vents were recorded: Mound 1 - 14.7 m; Mound 2 - 1.86 m; and Mound 3 - 1.22 m (north end) to 0.64 m (south end). Mound 1, which is adjacent to the Rabbitkettle River, is being undercut by a meander of the river. This is causing undermining and collapse of the riverbank and subsequent collapse of the mound. If this continues the river could eventually erode the mound completely and

therefore the condition of the bluff under the mound should be monitored. Ford (1974) suggested that some defensive works may be necessary but arguments will be presented below suggesting that such action may be contrary to Parks Canada policy

Other Hot Springs

As previously mentioned Rabbitkettle Hot Springs are unique in Canada in that no other hot or thermal spring, with the exception of Old Pot Hot Springs, Nahanni National Park, have formed tufa mounds of Rabbitkettle's magnitude. Old Pot Hot Springs, located at 61°31N, 126°30'W, near the Flat River, gushes in great volume to fill a large pond and several high walled deposits of tufa, or "pots", are present (Scotter et al, 1971). As with Rabbitkettle Hot Springs the water expelling from Old Pot is warmed by a geothermal gradient between the country rock (limestone) and a Cretaceous granite batholith. Also in this category are Wild Mink Hot Spring, 61°25'N, 126°35'W, situated near the Flat River and unnamed springs located near Hole-in-the-Wall Lake.

Scotter et al (1971) termed these "anomalous" thermal springs because they are probably heated by the chemical reaction of the water with minerals in the bedrock through which they passed. The other type of hot spring classified by Scotter et al, (1971), found in Nahanni National Park is the "normal" thermal spring found at Kraus Hot Springs

upstream from the junction of Clausen Creek and South Nahanni River.

Apart from those in the Nahanni Region thermal springs are common in the Western Cordilleran Mountains (Harrington, 1970; Van Everdingen, 1972) and in the U.S.A. (Yellowstone National Park, Saunder, 1970). Not all Hot Springs form tufa mounds similar to those at Rabbitkettle but the most notable of those that do are:

1. Mammoth Hot Springs, Yellowstone National Park
2. Besenova, Czechoslovakia. (Silar, 1968).
3. Rotomahana, New Zealand (Holmes, 1964).

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I. CHAPTER 1

A. LITERATURE REVIEW

Previous Work on Thermal Springs of the World

Thermal springs are widely distributed throughout the world but are most numerous in areas in which there has been volcanic activity in late geologic time. Hence, it is not surprising that numerous articles on thermal springs have been published. Waring (1964), in his review of available literature referenced three thousand seven hundred and thirty-three published papers concerning thermal springs around the world. (In the interests of brevity, these will not be discussed in detail.) Many more have since been published. Many of these papers are about geyser activity or therapeutic values of the thermal waters. As these have little relevance to the formation of the Rabbitkettle Hot Springs most were not reviewed.

Day and Allen (1924) studied the source of the heat and water in the hot springs in the Lassen National Park, California and produced one of the earliest reviews of this nature. They discovered that the hot springs are fed chiefly by surface water which drains the basin in which they lie and that the variation in the volume of the surface water locally and seasonally accounts for the variations in volume and the greater part of variations in temperatures of the springs. Minor amounts of water may be of magmatic origin. They also concluded that steam given off by magma is the

source of heat of all the hot springs in Lassen and Yellowstone National Parks.

Waring (1965) stated that most investigators of thermal springs believe that almost all of the water is of meteoric origin. This is certainly the case at Rabbitkettle (see below).

Saunders (1970), in his work at Yellowstone, discussed the difference between hot springs and geysers and the ideal conditions associated with these for carrying out experiments in cloud dynamics, cloud seeding and ice-crystal growth. He stated that hot springs are similar to geysers but the temperature is prevented from reaching values high enough for geyser action. Saunders (1970) suggested that water beneath the surface becomes heated and convection forces the water towards the surface. This may occur to some extent at Rabbitkettle but the major force which raises the water to the surface is hydraulic head. Ford (1974) suggested that the waters at Rabbitkettle are at or very close to the lowest place, in topographic terms, at which water circulating in these rocks could discharge.

Many workers describe individual regions with hot springs. Banerjee (1965) described the hot springs of India, presenting the physical and chemical data from the springs. Data included measurement of radioactivity of the spring water, spectrum analysis, bacteriological analyses, nature of water with low and heavy minerals content and the interpretation of chemical analyses of mineral spring

waters.

Mazor and Verhagen (1976) described the hot springs of Rhodesia and investigated their chemical properties. Tritium contents indicated that the waters were from indigenous deep-seated sources. Noble gas measurement revealed that the waters are meteoric. Palaeotemperatures and stable isotopes independently indicated the meteoric origin of the springs. Stable isotopes were used to determine the meteoric origin of the Rabbitkettle Springs.

The literature was searched for publications concerning hot springs that formed large tufaceous mounds as at Rabbitkettle. A colour poster was found which showed a tufaceous mound formed by thermal waters in Afghanistan which was at least 100 m high but no reference to this mound was found in the literature. Holmes (1944) mentioned the large white terraces of Rotomahana Hot Springs, North Island, New Zealand which were of a similar size to those of Rabbitkettle. The Rotomahana terraces were destroyed by explosions during the catastrophic Tarawera eruption of 1886. Martin (1887) described these terraces:

> "The largest and most important structure, but lately so well known as the White Terrace, was of very recent geological formation. Its origin, the Terata Geyser, was situated in a crater-like hollow near the centre of a conical hill of steaming and partially decomposed feldspathic tuff on the south-east side of the warm Lake Rotomahana.

> Outspreading fan-like from its cauldron, 100 feet (30 m) above the lake, and descending by terraced steps of white sinter in a sector of 60^0 its a broad flat of indurated mud, it encroached upon the lake with a wide sweeping curve measuring 800 feet (240m). The distance from the apex to the frontage was equal to a radius of 800 feet (240m), and the measurement gives an area of about 32,000 square feet (2976 square meters) or about 7 1/4 acres (18.125 hectares)."

The famous Mammoth Hot Springs, in Yellowstone National Park, have been known for a long time and much has been published about them. Weed (1889) stated that while calcareous hot waters are not rare in nature and are usually surrounded by travertine deposits, often of considerable extent, there are few places where such deposits equal those of the Mammoth Hot Springs in magnitude. The total area covered by travertine is about 2 square miles (about 5 sq km) and the greatest thickness is probably about 250 feet (76.25 m), but the average is much less. The upper limit of the deposit forming terraces is 1400 feet (427 m) above the Gardiner River; the travertine extends from this terrace down to the river, forming a continuous covering of varying width and thickness.

Weed (1889) claimed that only two other hot spring terraces rival those of Mammoth, namely, the travertine deposits of Hierapolis in Turkey and the springs of Hammon

Meschoutin in Algeria. Silar (1968) mentioned that the travertine terraces at Besenova Czechoslovakia resemble those at Mammoth in appearance but are much smaller. Baker (1968) mentioned the thermal springs near Midway, Utah. Here the calcareous tufa covers an area of 11.65 square kilometres and is locally at least 21.35 m thick. Solid mounds of tufa can be as much as 3m high.

Previous Work on High Latitude Thermal Springs:

The literature was searched for references to high latitude hot springs to find any relationship between thermal spring deposits and patterned ground. In Canada Rabbitkettle is the only mound of its size which has patterned ground formed on and associated with its calcareous deposits.

The Russian literature proved uninformative on any connections between patterned ground and hot springs. Due to language problems much of the Russian literature remains untranslated and so may contain references to this association. However, the articles which were translated made no reference to patterned ground associated with thermal springs .

Raik (1966) mentioned that tufa mounds (geyserite) occurred around some of the thermal springs in the Kamchatka peninsula, U.S.S.R. but made no mention of patterned ground formed on them. Golovachev (1937) summarised the properties of the mineral springs of the south-eastern extremity of the Chukchee Peninsula, U.S.S.R. While some of the waters have

temperatures up to 78°C none have formed large areas of calcareous deposits. Golovachev (1937) appeared more concerned with their therapeutic values and does not mention any patterned ground associated with them. Concerning the Chaplino group of mineral springs he stated (p 76):

> "Mineralized waters of such properties are prescribed according to L.I. Veingerov in such illnesses as syphilis, chronic mercury, arsenic or lead poisoning, in ailments of the joints, bones and muscles; in various skin diseases: scrofula, gynecological disorders; and certain diseases of the heart."

Nikolski (1937) described travertine deposits surrounding some of the hot springs in the district of the Gulf of Lavrenty and the Mechigmensk Bay, Chukckee Peninsula. No mention of size of the travertine deposits was made nor of any associated patterned ground. He did outline their chemical analyses, especially the radium and thorium content.

Hot spring mounds of Rabbitkettle scale are apparently unknown in high latitudes. Nowhere in the literature was there any reference to a travertine/tufa mound greater than 15 m high (Rabbitkettle's size).

Canadian Hot Springs

No thermal springs have been recorded in eastern Canada and less than fifty are known at present in western Canada; most of these are in British Columbia. They seem to be

associated chiefly with faults in ancient sedimentary strata or with fissures and fractures in the Mesozoic and Cenozoic granitic and metamorphic rocks.

The earliest work done on hot springs in Canada was by Satterly and Elworthy (1917) and concerned the chemical character of selected thermal and mineral springs. These included some mineral springs in Ontario and Quebec.

In 1926 Elworthy produced a report on the radioactivity and chemical properties of hot springs in western Canada. This was the first thorough publication on physical and chemical aspects of western Canadian hot springs. Four localities were chosen for complete field tests including properties such as temperature, flow, radioactivity and chemical properties such as colour, turbidity, taste, specific gravity, salinity, alkalinity and various chemical constituents. The four localities were Radium, Fairmont, Halcyon and Harrison Hot Springs. To make the report more comprehensive, Elworthy (1926) added information on the hot springs near Jasper, in the Lillooet River and on the British Columbia coast.

Van Everdingen (1969b) produced a paper concerning the degree of saturation with respect to $CaCO_3$, $CaMg(CO_3)_2$ and $CaSO_4$ for some thermal and mineral springs in the southern Rocky Mountains. He studied the major ion composition of spring water and produced formulas for the calculation of Ion-activity products and saturation degrees of the spring waters. He used this data for a comparison of the thermal

and mineral springs of this region.

Van Everdingen has published many papers on individual hot springs. Van Everdingen (1970) looked at the physical and chemical characteristics of the Paint Pots, Kootenay National Park, B.C. These are acid spring waters with extreme heavy-metal content. In 1969(a) he published a paper on the Ink Pots near Banff, Alberta which he classifies as karst springs. Both of these are summarised in Van Everdingen's (1972) report for Environment Canada.

Recently the main work on hot springs in Canada was done by Van Everdingen (1972) who completed a report on "Thermal and Mineral Springs in the Southern Rocky Mountains of Canada" for Environment Canada. He divided the Rockies into four regions; Banff National Park, Jasper National Park, Kootenay National Park and the region south of Kootenay. He analysed each region separately in terms of geologic structure, possible source of waters and mechanisms for heating. Then individual springs were analysed for Ca, Sr, Mg, Fe, Mn, Al, Cu, Zn, Pb, Na, K, Li, HCO_3, SO_4, Cl, I, Br, F, PO_4, NO_3, SiO_2, H_2S, CO_2, dissolved O_2, pH, Eh, conductivity, temperature and discharge.

Other literature used in this study will be referenced in the section to which it is relevant.

Nahanni Region

There are not many published reports concerning the Nahanni Region. In scientific fields the earliest published report was by Snyder (1937). This report refers mainly to

general features and shows "Rabbitkettle" at the site of both the lake and the Hot Springs. His account was based on observations made during a flight from Fort Simpson to Glacier Lake.

Raup (1947) studied the botany of the Southern Mackenzie Mountains which includes part of the Nahanni region. Since 1947 a number of botanists have studied areas in the Nahanni including the Rabbitkettle district. Cody and Spicer (1967) compiled a list of plants collected at Rabbitkettle Lake and in 1972 Cody and Brigham did the same for the Rabbitkettle Hot Springs cone. Scotter et al, (1971) completed a report on the ecology of the South Nahanni and Flat Rivers area for the National and Historic Parks Branch. This was used as a basis for setting up the Nahanni National Park in 1974. Scotter and Cody (1976) produced a paper on the 483 vascular plant species of South Nahanni National Park.

In the geologic and geomorphologic fields the first account of the Nahanni region was by Gabrielse, et al, (1965) who mapped the geology of the Flat River, Glacier Lake and Wrigley Lake areas in the Mackenzie Mountains.

Ford (1974) completed a report for Parks Canada on the geomorphology of South Nahanni National Park, as a guideline concerning the natural resources within the newly formed park. He included a brief account of the Rabbitkettle Hot Springs. Ford (1976) noted evidence of multiple glaciation in the South Nahanni National Park but emphasised that the

interpretation was preliminary because very little detailed study has been conducted outside of First Canyon (Figure 02). This paper and further descriptions of the Nahanni landscape were summarised by Ford (1977).

Van Everdingen (1973) analysed the thermal and mineral springs of South Nahanni National Park. His data for the trace elements in Rabbitkettle Hot Spring waters are used in this thesis.

The most recent report concerning the Rabbitkettle area was by Marsh and Scotter (1976) prepared for Parks Canada. This was a vegetation survey but included recommendations for development of the Rabbitkettle Area.

II. CHAPTER 2

A. METHODOLOGY

Methodology in the Field

1. Mapping: The area of the springs and deposits was mapped by plane table triangulation. Sightings were made with an alidade and angles of slope with an abney level. A compass was used for orientation.

2. Spring waters: Samples of spring water were taken at various intervals throughout the field season. The containers used for sampling were made of glass or polyethylene with 250ml capacity. The bottles were rinsed in spring water prior to sampling and then samples were taken immediately. The bottles were sealed under water to avoid contamination or diffusion of some of the elements.

   The temperature of the springs was measured with a YSI telethermometer which was calibrated with a Sargent and Welch mercury in glass thermometer. The glass thermometer was used also to check the YSI telethermometer's readings.

3. Discharge: Many problems were encountered in obtaining discharge readings from the vents of the three mounds. The discharge from Mound 3 was found to be totally impossible to gauge as water flowed out in numerous directions and evaporated. Mounds 1 and 2 had very small and shallow outlets so the installation of a V-notch

weir was impossible. Furthermore, Mound 1 had up to four small discharge outlets, operating simultaneously, which further complicated the measuring of discharge.

Many ways of measuring discharge were considered. First, one could pump out water so that the surface of water in the vent would be lowered. Then, by pumping to keep the level constant, discharge could be measured. The problem with this method was a logistic one, that of acquiring a pump and transporting it to the hot springs.

The second idea was to inject a known concentration of dye (Rhodamine WT) into the water at the base of the vent, mix it and allow it to flow up to the surface. The concentration of the dye at the surface over time would be proportional to discharge. However, this method would have caused contamination of the mound surface by dye. A similar experiment using salt instead of dye might be feasible.

It was realised later that there is some throughflow of water through the tufa and so the water discharging at the top is not the total discharge. Bearing this in mind, it was decided to proceed and estimate discharge at the surface of the vent. This was accomplished by placing a plastic sheet on the tufa at each of the outlets. The point of the sheet at the outlet was pressed down on the tufa so that minimum water would pass underneath and therefore most of the water from the outlet flowed onto the plastic sheet, and

was channelled to a specific point at the opposite end. Here the water flowed into a plastic garbage bag which was allowed to fill for a specific time and then withdrawn. Discharge was calculated from the volume of water in the bag over a certain time. The volume of water in the garbage bag was measured with a graduated cylinder. This was done at each outlet and the sum of the discharges totalled.

Two problems must be kept in mind; first, the flow off the plastic sheet must be constant before timing begins; and second, some flow does escape underneath the plastic sheet. It was estimated, however, that at least 80 percent of total water from each outlet was caught in the garbage bag.

4. Other field chemical analyses: pH was measured with a ph meter and litmus paper. Conductivity of the waters was measured with a Beckman Solubridge type RB3-338, portable conductivity bridge (by R. Wickstrom, Canadian Wildlife Service). Transparency was measured with a secchi disc (by R. Wickstrom, Canadian Wildlife Service).

Methodology in the Laboratory

1. Water Hardness determination: The samples taken were kept at a constant (room) temperature in order to keep the equilibria constant and avoid upsetting the hardness values.

   In the laboratory the following apparatus and

chemicals were required: burette, 25ml pipette, retort stand, clamp, and boss, two 50ml conical flasks, polythene wash bottle 250 ml, EDTA titrating solution N/50, Ca indicator: Ammonium purpurate, Mg indicator: Solochrome Black, Ca buffer: Sodium Hydroxide and Mg buffer: Ammonium solution.

EDTA solution was placed in the burette and 25ml of sample were pipetted into a 50ml conical flask. Ca buffer and indicator were added to the sample which turned a claret-red. EDTA was titrated into the sample until the sample turned a pale blue. Titration was immediately stopped and the amount of EDTA used recorded. Each sample was titrated three or four times to minimise error and the mean of the results calculated. This result is the Ca hardness.

A further 25 ml of the same sample were pipetted into another conical flask and Mg buffer added. The amount of EDTA used in the Ca hardness test was then titrated and Mg indicator was added. The sample initially turned black. Titration was continued until the sample turned transparent, and the amount of EDTA used recorded. The amount of the difference was divided by 4 to determine Mg hardness (4 parts Mg to 1 part Ca).

Calculation of the Results:

if volume of EDTA titrated = x
volume of sample = 25 ml

$$\text{Ca hardness} = \frac{\text{titration in ml} \times 1000 \text{ ppm } CaCO_3}{\text{volume of sample in ml}}$$

$$= \frac{x.\ 1000 \text{ ppm } CaCO_3}{25}$$

$$= x.\ 40 \text{ ppm}$$

$$\text{Mg hardness} = \frac{\text{Total hardness} - \text{Ca hardness}}{4}$$

$$\text{Total hardness} = \frac{\text{Titration (second one)}}{25}$$

$$= y.\ 40 \text{ ppm}$$

$$\text{Mg hardness} = \frac{y - x}{4}$$

2. Isotopic Analyses of the Waters: (These analyses were performed by Dr. P. Thompson, Department of Physics, University of Alberta). The hydrogen composition was measured by reacting 20 microlitres of water with uranium at 750°C. Oxygen isotopic compositions were measured by equilibrating CO_2 with 5 mls of water at 25.2°C. The fractionation factor between CO_2 and H_2O at this temperature is 1.0412.

3. Trace Elements: Water analyses were performed by the Calgary Laboratory of the Analytical Services Station, Water Quality Branch, Inland Waters Directorate, Environment Canada, using standard methods (Traversy, 1971). Results of these analyses are reported in parts per million (ppm) or milligrams per liter (mg/l). Waters were sampled by R.O. Van Everdingen and results reported are for his samples from June, 1973.

4. Geochemical analyses of spring deposits:

   Samples of the spring deposits at Rabbitkettle Hot Springs were analysed by X-ray diffraction in the Department of Geology, University of Alberta, under the supervision of Dr. H. Baadsgaard.

5. Grain size analyses of small particles in patterned ground: Apparatus used included a Mettler Type H4 balance, 4mm, 2.83mm, 2mm, 1mm, and 1ϕ sieves and an oven. Samples of patterned ground particles were dried thoroughly. A representative sample of the amount required to perform the tests was selected by the method of quartering. This representative sample was then weighed. The particles were separated into different sizes by sieving through the above sieves for a period of 10 minutes. Portions of a particle size fraction were individually weighed and this weight was calculated as a percentage of total weight.

6. Statistical Analyses of Physiographic Relationships: Two analytic techniques were used: correlation - the Pearson

r test, to measure the relationship between two variables. The formula used here is:

$$r = \frac{\Sigma z x z y}{N}$$

where z = the standard score and N = number of data points used. The other analytic technique was linear regression. The formulae used were:

$$b_{yx} = \frac{\Sigma XY - [(\Sigma X)(\Sigma Y)/N]}{\Sigma X^2 - [(\Sigma X)^2/N]}$$

$$a_{yx} = \bar{Y} - b_{yx}(\bar{X})$$

where X = the mean of X, Y = the mean of Y, X = the sum of the scores of X, Y=the sum of the scores of Y, and N = the number of cases.

III. CHAPTER 3

GEOLOGY

The geology of the region surrounding the Rabbitkettle Hot Springs has been investigated by various authors including Gabrielse et al, (1963) and Ford (1974). The former described the bedrock geology of the Rabbitkettle River valley and the Hole-in-the-Wall Creek valley and also the surrounding Flat River, Glacier Lake and Wrigley Lake areas of the District of Mackenzie and Yukon Territory. A knowledge of the bedrock geology of these river systems is essential to an interpretation of the surficial deposits underlying, and surrounding, the Rabbitkettle Hot Springs. Gabrielse et al, (1965) recognised five main geologic units in this area which are termed Units 18, 20, 23, 35 and 36 on the geologic map (Map 1).

The uppermost unit in the stratigraphic column, exposed at Rabbitkettle, is unit 36 which is of Pleistocene and Holocene age. This unit consists of unconsolidated glacial and alluvial deposits and is exposed mainly along the valley bottoms of both these rivers. The hot springs mounds at Rabbitkettle are situated on fluvial deposits of this unit.

Upstream from the hot springs, in the vicinity of Mount Sidney Dobson 61°58' N, 127°32' W, and in the headwaters of Hole-in-the-Wall Creek are outcrops of unit 35, which are medium to coarse-grained granitic rocks. These are in the form of two batholiths and numerous stocks in Glacier Lake area (62° to 63°N and 126° to 128°W). The granitic rocks

consist mainly of quartz monzonite and granodiorite; being differentiated on the percentage of free quartz crystals available in the magma at the time of crystallisation. Both of these commonly contain from 15 percent to 40 percent megacrysts of euhedral to subhedral potash feldspar, ranging from 1 cm to 6.5 cm long, in a medium to coarse-grained matrix of feldspar, quartz, biotite and/or hornblende (Gabrielse et al, 1963). A K/Ar date on the quartz-monzonite (Gabrielse et al, 1963) of the N.W. Flat River gives a Cretaceous age (110 million years). Ford (1974) believes that this batholith of quartz monzonite and granodiorite is responsible for the geothermal warming of the waters expelling from the hot springs. It should also be noted that other hot springs in the Nahanni region, Wild Mint, Old Pot and one near Glacier Lake, are also situated near the boundary between a granitic batholith and the country rock (Addison, W.D., pers. comm. 1978).

The country rock underlying the Rabbitkettle Hot Springs (unit 23; Gabrielseet al, 1963) is an Ordovician/Silurian, black, pyritic shale, which may be locally slaty or phyllitic. Sometimes it contains thin bedded, black argillaceous limestones, beds of grey and black chert, calcareous siltstones and/or black cherty dolomites. Near the granitic intrusions the country rock becomes more resistant as a result of metamorphism. Unit 23 outcrops in the vicinity of the hot springs and along the flanks of Hole-in-the-Wall Creek valley as far south-west as

Hole-in-the-Wall Lake.

Units 20 and 18 are exposed in the Rabbitkettle valley but not in the Hole-in-the-Wall Creek valley. Unit 20 is of Cambrian and/or Ordovician age and is best exposed to the west and southwest of the hot springs. The lower part of this unit (20a) is comprised of grey, slaty argillaceous limestones and buff calcareous slate which could be up to 100 m thick (Gabrielse _et al_, 1963). The upper part of the unit (20b) includes banded, buff and grey weathered blocky, dark grey, crypto grained limestone about 75 m thick. Unit 18 is of Middle Cambrian to possibly Upper Cambrian age. The lithology of this section is intercalated platy, impure limestone and siltstones found west of Rabbitkettle Lake. These beds are up to 1200 m thick. The lowest member contains more siltstone and silty limestone while the upper one consists of light grey, weathered, dark fissile argillaceous limestone and calcareous shale and occurs to the southwest of Rabbitkettle River.

Ford (1974) states that the hot springs at Rabbitkettle are situated at the northern tip of the quartz monzonite injection of the Nahanni Aiguilles formation and believes that the hot water is discharging from the monzonites. Granitic rocks, however, have a low primary permeability and also a low primary porosity. On the other hand granitic rock may have high secondary porosity and permeability which it may possess in the form of joints or fractures. Gabrielse _et al_, (1965) did not mention the structure of the quartz

monzonites or the granodiorite and field observations of exposures of these rock units were limited. Hence two possibilities have arisen:

1. If these rocks are heavily jointed and fractured they possibly have a high secondary permeability. The water, which is meteoric has flowed along the hydraulic gradient into the fractures and joints of the granitic batholith and has been heated by the last vestige of crustal energy that injected this plutonic rock (Ford, 1974). Therefore, the springs are at or very close to the lowest place, in topographic terms, at which the water could discharge (Ford, 1974).
2. Having few or no fractures, these rocks would act as an impermeable boundary and so water flowing along the hydraulic gradient through the country rocks would be forced upwards at this boundary and would discharge at the surface. Heat from the batholith would result in the warm temperatures recorded at the hot springs. It is not known from what depth the hot water comes but some cooling would occur on its passage upwards. Van Everdingen (1972) noted at the Upper Hot Springs, Sulphur Mountain, Banff, Alberta, that the water cools gradually on its way to the surface through contact with cooler rocks.

GEOMORPHOLOGY

The glacial geomorphology and chronology in the many ranges of the Mackenzie Mountains are poorly known and very

little detailed study has been conducted outside of the First Canyon on the South Nahanni River and a few other localities. Ford (1976) identified three distinct zones of glaciation:

1. Cordilleran glacial zone, extending from the western limit of the Nahanni National Park to the western edge of the Funeral Range.
2. Laurentide glacial zone, extending from the eastern limit of the Park to the eastern flanks of the Nahanni Plateau and Tlogotsho Range.
3. Central unglaciated zone, which lies between the Funeral Range and Nahanni Plateau.

The Rabbitkettle Hot Springs region is associated with the Cordilleran glacial zone. In the Ragged Range there is much erosional evidence of alpine glacial activity, including cirques, horns, aretes, cols, tarns and riegel, valley steps and paternoster lakes, which reflects erosion by late Quaternary glaciers which were temperate at the sole (Ford, 1976). There are unvegetated moraines of the "Little Ice Age" in the west of the Range where the mountains are higher. The Ragged Range is upwind of the predominating air flow and so take much of the precipitation from these winds, accounting for stronger glacial activity in the Ragged Range.

The Nahanni "Cuillins", as Ford termed the unnamed mountains 10 km east of the Ragged Range, are downwind of the Range, which implies that much of the precipitation has

been intercepted and they also have a lower crestline (ca. 500 m lower). Hence, there is a sharp glacial morphologic contrast between the two ranges with dissection being much less intense in the Cuillins; gentle unbreached crestlines rather than horns and aretes. The west facing upwind flank of the Cuillins is dissected by smooth-floored glacial valleys ending in troughheads rather than cirques. Ford (1976) believes that the related glaciers were of a more "polar" thermal regime.

The synclinal Hole-in-the-Wall Creek valley lies between these two ranges. The latest valley glaciers from both of these ranges made small advances down this valley. Large lateral moraines are preserved along the valley; some having been breached by the marginal meltwater channels of the valley glaciers.

Ford (1976, 77) believes that the Ragged Range and the west flank of the Cuillins experienced small glaciations during Classical Wisconsin time with maximum penetration of 6 km into the lowlands. This interpretation was based on a comparison with fresh glacial morphology in Europe and elsewhere in North America. The Ragged Range has similar glacial morphology to the Alps which experienced the European equivalent of the Classical Wisconsin, the Wurm. Breaches in the divide near Rabbitkettle indicate that the snouts of these glaciers must have been at 1100 m above sea level at one time.

Therefore direct glacial activity appears to have had

little effect on the landscape development at the hot springs during the most recent advance, as the Cordilleran glaciers did not reach the hot springs (Marsh and Scotter, 1976; Ford 1974, 76, Figure 3:1). Ford (1974) reports the discovery of a glacial till under the south hot spring mound (mounds 2 and 3). Field investigations show that these mounds are built upon a glacial till which also forms the elevated areas to the east and the south (Figure 3:2).

Air photograph interpretation of this area shows the extent of the glacial till. The till forms the upland areas surrounding Mound 2 and 3 and appears to be incised by a fluvial channel. This process would have removed some of the till from the area between these mounds but the lesser elevated area under Mounds 2 and 3 would appear to be a continuum of the till deposit.

The till consists of varying sizes of particles from a silty clay matrix to large boulders metres in diameter. The large particles are largely of granitic origin, due to the resistant nature of the rocks, while the small particles are largely derived from chert, slate, slaty shale, shale pyrite, quartzite, limestone, dolomite, quartz monzonite and granodiorite. Some of the particles show varying degrees of weathering, especially the small granitic pebbles, indicating their probable deposition during an earlier glaciation than the Hole-in-the-Wall Glaciation (Table 1).

This deposit of till was probably incised when the Hole-in-the-Wall Creek breached the mountain spur and flowed

into the Rabbitkettle River in the vicinity of the present location of the hot springs. Today the Hole-in-the-Wall Creek breaches the same spur farther east and flows into the Rabbitkettle River downstream from the hot springs. Another possible explanation for this feature (the valley in the till) is that it was formed by one of the meltwater channels from the latest glaciations mentioned above. Whether it was formed by a shift of the Hole-in-the-Wall Creek, or by a meltwater channel from the Hole-in-the-Wall Glaciation, a V-shaped valley has been incised into the till found to the south of vent 3.

Ford (1974, 76)mentions the discovery of lacustrine deposits in the South Nahanni River valley (Figure 3:3). There are two main depositional areas:

1. West of Third Canyon to a point 40 km upstream of Virginia Falls and in the Flat River valley almost to the Park boundary. This deposit reflects inundation to 650 m a.s.l.
2. In Deadman Valley and Clausen Creek area.

The former lake sediments are relevant to landscape development at the Rabbitkettle Hot Springs. These belong to Glacial Lake Nahanni, formed by ice-damming probably late during the Illinoian Glaciation. Evidence for this age is given by dating speleothems in the north karst of First Canyon region (Ford, 1976) using the $^{230}Th/^{234}U$ method which placed the Glacial Lake Nahanni development around 145,000±6000 years B.P. The Glacial Lake Tetcela sediments

were found to be younger than 30,000 years B.P. using this method of dating (Ford, 1976).

Deposits from Glacial Lake Nahanni (Figure 3:3) are dominantly buff-weathered and have little bedding structure when seen at a distance; although close inspection at some sites reveals fine laminations. The material appears to consist mainly of clay with lesser silt and scattered dropstones (Weirich, 1976). Some coarse sands and fine gravels with deltaic structures occurs in places at the margins. All trace of these sediments above 40 km northwest of Virginia Falls has been erased by the subsequent meandering of the river except at Rabbitkettle where 30 - 40 m of grey silt on a cobblestone base is found at 660 - 680 m. Ford (1976) believes this may be part of a delta facies.

Ford (1974) noted two terraces, which form the local upland at Rabbitkettle Lake, at 24 m and 15 m above the South Nahanni River and believed these are remnants of deltaic deposits. At the hot springs two terraces were found; the lower one at 6 m above the Rabbitkettle River (August flow height) upon which Mound 1 is situated; and an upper terrace at 20 m is found on the opposite bank to the hot springs 100 m downstream.

Samples were taken of the terrace deposits beneath Mound 1. A list of sediment size and lithology is recorded in Appendix 1. The sediments were gravel to cobble size particles, up to 9.2 by 6.5 by 2.9 cm ("a" axis by "b" axis by "c" axis), which would indicate a high energy flow of the

stream that deposited these sediments. Bedding was not observed, nor any structure, but this may have been obscured by the thick calcite coating deposited on the sediments by percolation of supersaturated water down from the hot spring.

All the particles are well rounded indicating that they have been water transported. Some of the small particles (pebble size) have been calcited together to form a tufa conglomerate. It was also noticed that some particles were very weathered and oxidised and a few displayed weathering zones.

The large water-rounded granite boulders, found adjacent to Mounds 2 and 3, and also in tufa areas "a", "b", "c" and "e" (Marsh and Scotter, 1976, map), were suggested by Ford (1976) to have been ice rafted. The present day Hole-in-the-Wall Creek, however, carries boulders equally large in its stream and so it is quite feasible that these large granite boulders were, in fact, transported by the old Hole-in-the-Wall Creek, if not the Rabbitkettle River. A direct glacial origin is also conceivable in the form of a till.

This account is based upon previous geomorphological work done in the region (Ford 1974, 76, 77; Marsh and Scotter, 1976; Weirich, 1976) and field observations in the summer of 1978. It should be emphasised that it is a preliminary account for the glacial and fluvial history of the Rabbitkettle Hot Spring area is complex.

CLIMATE

The climate of Nahanni National Park region has been studied on various occasions (Raup, 1947; Burns, 1973; Scotter and Cody, 1974). Burns (1973) presented the most comprehensive estimate of the climate and this was used by Marsh and Scotter (1976) for their study of the vegetation of the Rabbitkettle area. During the field season of 1978 temperatures were measured on a regular basis by National Park staff at Rabbitkettle Lake and these readings are shown in Figure 3:4). Relative humidity (Figure 3:5) and minimum and maximum temperatures were recorded by a thermohygrograph. Temperatures were also measured at the hot springs on a regular basis using a Sargent and Welsh mercury in glass thermometer placed in a shaded position.

Table 2 shows estimations by Burns (1973) for mean daily temperatures for the Rabbitkettle locality and on an annual basis it has been noted that the mean daily temperature at Rabbitkettle is 2.8^{0}C cooler than that at Virginia Falls (Marsh and Scotter, 1976). Table 3 shows precipitation in amount and occurrence in the Rabbitkettle, Virginia Falls and Fort Simpson localities (Burns, 1973).

During the 1978 field season the mean daily maximum for July was 21^{0}C at the hot springs, with maximums in late July and early August around 30^{0}C. Even with these high maximums during the day, the night time temperatures are low; occasionally below 0^{0}C. January temperatures can be as low as -48^{0}C (Scotter and Cody, 1974) rarely rising above -18^{0}C.

Annual precipitation at Rabbitkettle is generally higher than in the rest of Nahanni National Park with a mean of 76 cm (Burns, 1973).

It was noticed, however, that due to the situation of Rabbitkettle Hot Springs at the junction of two valleys the weather systems are profoundly influenced by the local topography. Marsh and Scotter (1976) summarised the local weather at Rabbitkettle Lake in relation to major weather systems as:

1. A high pressure system over the Yukon and a convectively unstable airmass over the Park produces light westerly winds at Rabbitkettle in the early morning increasing in strength throughout the day. By noon cumulus clouds have built up over the mountains and drift eastward. Afternoon showers caused by this convective turbulence increase the westerly winds at the surface causing strong west or northwest winds. These eventually decrease by midnight.
2. When uprising unstable air from the east arrives in the area the gentle upslope flow during the morning produces cumulus clouds. The thunderstorm activity, associated with the cumulus clouds which develop by midafternoon, produces gusty west winds of short duration. These revert to light easterly winds again with the passage of the storm.
3. A cold front from the north pushes a high pressure system up the Mackenzie Valley causing upslope

conditions over Nahanni, in turn producing up to three days of cool, rainy weather.

4. A cold, low pressure system from the west will produce precipitation in the Park.
5. A low pressure system centred near the 60th parallel and moving eastward produces precipitation that lingers longer in Nahanni National Park than at Fort Simpson. The low cloud formed by such a system is pushed up the Nahanni by the easterly upslope wind and is only flushed out by a strong westerly wind.

VEGETATION OF THE RABBITKETTLE REGION

The vegetation of the South Nahanni River area is not well documented. Detailed plant cover descriptions are available for only three small regions: Glacier Lake (Raup, 1947), Hole-in-the-Wall Lake (Arnold, 1961) and the Rabbitkettle area (Marsh and Scotter, 1976). Rowe (1972) placed the Rabbitkettle area in the Alpine Forest-Tundra Section of the Boreal Forest Region. An altitudinal transition is seen from the closed forests in the lowlands to alpine tundra on the mountains. The treeline is between 1,100 m and 2,000 m depending on aspect. Rowe (1972, p. 73) describes this vegetation as "open park-like stands of stunted white spruce alternating with patches of grassy or shrubby vegetation . . . characteristic of mountain slopes . . ." This description is roughly applicable to the climax vegetation of the terraces at Rabbitkettle Lake. Although the dry south slopes have patches of shrubby or grassy

vegetation, the white spruce is far from being stunted.

The dominant trees are white spruce (Picea glauca) and balsam poplar (Populus balsamifera) in undisturbed stands rather than mixtures (Rowe, 1972). Trembling aspen (Populus tremuloides) occurs in some places especially those which were subjected to the fire of 1949 (Marsh and Scotter, 1976).

Marsh and Scotter's (1976) map (Figure 3:6) shows that in the vicinity of the hot springs the major species is white spruce (Picea glauca) while to a lesser extent the lower, damp, marshy areas are colonised by black spruce (Picea mariana) and labrador tea (Ledum groenlandicum). Also surrounding the hot springs are minor communities of Willow (Salix spp) and dwarf birch (Betula glandulosa) found on the dry, west-facing, burned slope on the top of the well-drained Mountain spur southwest of Mound 1; grassland vegetation on the south facing slope of the ancient Hole-in-the-Wall Creek channel southwest of Mound 3 (Table 4 shows Marsh and Scotter's (1976) percent frequency and cover of shrubs, herbs and ground in the community); and also some sedge (Carex spp) in the wet meadows of the ancient Hole-in-the-Wall Creek bed. Tables 5, 6 and 7 show Marsh and Scotter's (1976) percent frequency and cover of shrubs, herbs and ground for Black Spruce/Labrador Tea community in low marshy regions, for White Spruce community and for White Spruce/Black Spruce community on the till deposits west of Mound 2, respectively.

A detailed description of the vegetation and its influence on the mound genesis and morphology will be discussed in Chapter 6.

IV. CHAPTER 4

ORIGIN OF MOUNDS

Ford (1974) stated,

> "In their own right, hot springs are a special hydrological phenomenon and not of immediate interest to the geomorphologist. The vulcanologist is interested in them because they imply high temperatures, and therefore high energy situations, in the shallow crust. A report might treat them, therefore, in sections on hydrology or on tectonism. But where the springs create erosional forms such as the caves at Radium, B.C. or build up depositional mounds by rock precipitation such as at Rabbitkettle, they may be considered to be a special case of pseudo-karstic development."

Therefore it can be argued that the Rabbitkettle hot spring mounds are a precipitational feature comparable to those within karst regions; the formations being similar to the deposition of calcium carbonate within cave systems. The origin and chemistry of the waters resurging at the vents will be discussed later but here the ability of natural waters to dissolve or deposit calcium carbonate will be considered.

In order to appreciate the ability of water to dissolve/deposit calcium carbonate it is necessary to consider the chemistry of calcium carbonate. The actual process of reactions is complex but Stenner (1969) described

this by six equations:

$$H_2O \rightleftharpoons H^+ + OH^- \text{ ....(1)}$$

$$CO_2(\text{soln.}) + H_2O \rightleftharpoons H_2CO_3 \text{ ....(2)}$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \text{ ....(3)}$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{--} \text{ ....(4)}$$

$$CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{--} \text{ ....(5)}$$

$$CaHCO_3^+ \rightleftharpoons Ca^{++} + HCO_3^- \text{ ....(6)}$$

When the solution is in equilibrium with solid calcium carbonate the product of the concentrations of calcium ions (Ca^{++}) and carbonate ions (CO_3^{--}) is constant and the latter is related in turn to the concentration of the other species in solution. If more CO_2 is dissolved in the solution the concentration of carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-) will increase while that of carbonate will decrease. The equilibrium of equation number (5) is therefore unbalanced and the concentration of Ca^{++} must increase before equilibrium can be re-established. Therefore calcium carbonate must dissolve, and the solution becomes aggressive. The reverse applies to the diffusion of CO_2 from the solution, by which process calcium carbonates tend to be precipitated in order to maintain equilibrium.

In the case of the Rabbitkettle Hot Springs the warm water resurging at the vent is highly charged with $CaCO_3$ (340 - 440 ppm), $MgCO_3$ (180 - 200 ppm) and dissolved CO_2 (ca. 91 ppm). Upon leaving the vent some of the CO_2 is lost to the lower concentration of atmosperic CO_2 and part of the

high content of $CaCO_3$ and $MgCO_3$ is precipitated on the mound in order to maintain equilibrium in the solution.

Picknett (1964) calculated the concentrations of all species in a saturated solution of calcite at 10^0C and the relationship between "free carbon dioxide" (sum of dissolved molecular CO_2 and carbonic acid) and calcium (as Ca^{++} and $CaHCO_3^+$, Figure 4:1). This figure may be used to determine whether water is aggressive or not. It also shows that there is an exponential relationship between free CO_2 content and calcium content.

The Rabbitkettle Hot Springs are similar in morphology and formation to rimstone pools or gour pools in a cave environment. These involve a type of flowstone which occurs when supersaturated water with respect to $CaCO_3$ flows down the wall of the cave or over the floor depositing a thin layer of calcite. As the film of moisture or waters flow across the rock surface it loses CO_2 to the atmosphere due to its concentration gradient (lower CO_2 concentration in the cave atmosphere) and deposits $CaCO_3$ to maintain equilibrium. The growth is greatest where the film of water is thinnest, that is on the rim of a rock ledge or the edges of a projection. This is because on rock ledges or projections the water flowing over will have an increased surface area and hence more CO_2 can diffuse into the atmosphere. In rimstone pools the irregularities on the rock floor cause more CO_2 to diffuse and so more $CaCO_3$ will be deposited. Therefore a rim of $CaCO_3$ will build up over the

irregularity and this will be self-perpetuating as the higher the rim the more $CaCO_3$ will be deposited. The rims or dams cause pools to form behind them and so are called rimstone pools or gours. Another factor which will be discussed later is that the steeper the slope of the rock surface the larger the calcite rim (Figure 4:2) and that the ratio of surface area of pool to depth is much smaller than when the slope is gentle.

This is how the Rabbitkettle Hot Springs mounds have built up over time (Figure 4:3). Mineralized waters flow from the vent as a thin sheet or as shallow channelised flow. The small irregularities on the surface cause the water flow to thin in places. The precipitation rate is accelerated at the thinning point or along a line of thinning, thus building up a rim with a trough behind it. As the rim becomes higher the residence time of water within the pool (trough) is increased and so a greater part of its mineral content is extracted. This implies that the rate of deposition on the rim will eventually decrease and so the process is only self-perpetuating to a point. Eventually the troughs will infill by precipitation of $CaCO_3$ and also by airborne matter as they act as traps. When this happens the process begins once again with increased precipitation on the rims, thus building the tufa mound around the vent.

Ford (1974) suggests that the water will flow out in one direction at a time thus building up one segment of tufa. When this segment becomes higher than the surrounding

tufa surface it flows over the lower segment adjacent to it. Ford (1974) suggests that the flow thus rotates like clock hands around the mound. Field investigations and displacement tests show, however, that the flow does not rotate around the mounds in cyclic fashion but in fact flows into the lowest position on the mound. The displacement tests were conducted by placing a 0.15 m^3 mass into the orifice of Mound 1 so that the water level rose and spilled out over the tufa. The main spills occurred in two or three new channels apart from the northward route active at the time. These new channels were on the southeast side of the mound. This fact was confirmed by the presence of white, unweathered tufa in this area of the mound. Scotter and Marsh's (1976) report has a photograph of Mound 1 with water in the pools on the southeast side. The object used in the displacement test was removed at the end of the test. Analysis of the hydrogen isotopic composition versus oxygen isotopic composition of the waters from Rabbitkettle Hot Springs, however, shows that all the waters are of meteoric origin. These results suggest that the water expelled from the hot springs has only been in the ground for a short time.

Discharge readings suggest that the warm water expelling from the vents increases in flow slightly around August which suggests a lag time of greater than two months after peak seasonal discharge. Therefore, it is probable that water drains through the country rock from higher

elevations until it comes in contact with the quartz monzonite batholith where it is heated and forced upwards to the surface due to the impervious nature of this rock. Here the warm (21^0C) waters flow across the surface building up tufa mounds.

Physical Aspects of the Mounds

Various physical aspects of the hot spring mounds were observed. These included temperature of the water, transparency of the water, discharge, and the relationships between the slope of the mounds and pool width, thickness of tufa layers and distance from rim of pool, and pool width and rim height.

1. Temperature: This was recorded at various intervals throughout the field season by a YS1 thermometer and a mercury in glass thermometer (Sargent and Welsh). The results are listed in Table 8.

   There was little or no variation of temperatures throughout the field season. Descriptive temperature statistics for Mounds 1, 2 and 3 are shown in Table 10. The higher deviation and range size for Mound 3 may reflect the shallow nature of this pool where the water discharges. It was noticed that two days after a relatively warm day the temperature of vent 3 would rise and, similarly, after cool days it would drop. Discharge from vent 3 totally evaporates.

   Temperature at depth was also measured in order to find any variation. No variation was found in vent 1 and

the others were not examined as they are too shallow to affect temperature at varying depth (Table 9).

It was observed that the temperature varied slightly from one side of the pool to the other. In Mound 1 and Mound 2 this difference (approx. 0.1°C) is not considered to be significant but in Mound 3 it can vary up to 0.6°C. The higher temperature was recorded in the southwestern section of the pool where the depth is only 64 cm compared with a depth of 122 cm in the northeast where the water wells up. Therefore the shallow water responds slightly to external air temperatures.

2. Transparency: A transparency test was conducted on the waters in the orifice of Mound 1 by the use of a secchi disc (measured by R. Wickstrom). The secchi disc became obscured at a depth of 7.2 m. This implies that the water is very clear which would have been expected as it contains very few impurities or sediments.

3. Discharge: It should be realised that the figures listed in Table 11 do not refer to total discharge but an estimated 80 percent to 90 percent of total discharge from the vent orifice. On Mound 1, the four outlets were measured individually and their discharges added together to give total discharge (minimum) for the mound. Several readings were taken at each outlet and as some water is lost by flow under the sheet the highest reading in each case is taken.

Discharge increased slightly towards the end of the field season. The rise in discharge may be a result of lag time from peak seasonal discharge caused by snow melt. It is not certain as to the exact lag time involved but discharge appears to increase about two months after peak seasonal discharge in the local rivers. This indicates a lag of greater than two months.

Heavy rains had no effect on the discharge from Mounds 1 or 2 but were observed to affect Mound 3 which is not very deep (1.22 m) and has a shallow flow area. Rises in discharge in Mounds 1 and 2 were simultaneous which implies that they are connected to the same underground reservoir; a "U-tube" effect. This was not noticed at Mound 3 but factors such as evaporation and rainfall influence its discharge to a greater extent. It is assumed, however, that all three mounds receive water from the same source, as their geochemistry, temperatures and times of discharge increases are all similar.

4. Relationship between pool width and slope of tufa: It was observed that as the rimstone pool width became larger the slope of the mound became less; that is, the smaller the pool the steeper the slope on its upstream side. Sixty slope readings were measured by clinometer and compared with pool width (Figure 4:4). It was discovered that as the pool width increased the slope of the mound decreased (Figure 4:5). The correlation, the

Pearson r, was computed to be equal to -0.69. The readings are listed in Appendix 1.

5. Relationship between pool width and rim height: Warwick (1952), writing on rimstone pools in cave systems, noted that the steeper the slope is the larger the calcite rim (Figure 4:2). As shown earlier there is a relationship between slope and pool width at Rabbitkettle and thus there should be a relationship between pool width and rim height. Fifty measurements were made in the upper and lower sections of Mound 1 (these are listed in Appendix 2). The results were plotted on two graphs (Figures 4:6 and 4:7, for the upper and lower portions of the mounds respectively.)

    Linear regression analysis of both sets of data indicated that there is a linear relationship between pool width and rim height. In the upper portion, where rim heights are small in comparison to the lower portion a relationship of $Y=4.31 + 0.15X$ exists (Y = rim height and X = pool width (both cm)). For the lower portion the relationship was found to be $Y = 0.3 + 0.96X$. In lower portions of the mound, high rims appear to accompany wide pools.

6. Thickness of tufa layers: It was observed that as the angle of slope of the tufa increased on the outside of a rim the thickness of the tufa decreased. This was observed on all the rims that had slabs broken off (by frost shatter). This phenomenon is due to the fact that

more tufa is deposited on the top of the rims and will decrease in deposition as the water flows on the outside of the rim. At the top the surface of the water is convex which increases the surface area allowing more CO_2 to diffuse out and $CaCO_3$ be deposited. As the water flows down the outside of the rim the angle of slope increases and changes from convex to concave implying less surface area and subsequently less deposition.

It was also observed that when the angle of slope on the outside of the rim became 90^0 or greater curtain-like features developed in the tufa (Plate 2). These are similar to stalactite curtains in caves. At slopes of 90^0 or more the water no longer flows as a thin sheet down the tufa but falls off as droplets. Surface tension attracts water within a small area to one droplet. This accounts for the even spacing between curtains (Plate 2). Curtains are formed by drops of water trickling slowly down a steep surface depositing a line of $CaCO_3$ down the tufa which builds out in time to form a curtain-type formation (Figure 4:8). In Table 12 the measurements of tufa thickness in comparison with the slope angle of the rim are presented.

7. Other physical characteristics of the tufa mounds.
   a. The density of the tufa was found to be 1.3 gm/cc while the porosity is 0.7 percent.
   b. Slope of the mound was greater in the north, up to 35^0 in certain places compared with a maximum of 30^0

in the east and south. This is not a result of aspect, however, but rather would appear to be a result of the slope of the river terrace beneath the mound. This slope also accounts for the asymmetry of the mound (the distance from the vent to the north slope is greater than that to the east, south or west slopes). The terrace beneath the northern end of the mound slopes to the north whereas it appears level under the rest of the mound (Figure 4:9).

Chemical Aspects of the Rabbitkettle Hot Springs.

Various chemical aspects were researched and/or field tested. These included geochemistry and isotope geochemistry, pH, conductivity and dissolved O_2 and CO_2 of the thermal waters and the chemical composition of the tufa. Another chemical aspect was noted: the soft white precipitate on the southwest side of Mound 1.

1. Geochemistry: Numerous samples of hot spring water were taken throughout the field season. However, due to the lack of certain chemicals in the field, only hardness and isotopic analysis were conducted. The other results given are from Van Everdingen (1973).
   a. A total of 25 samples were analysed to evaluate the amount of calcium and magnesium ions in solution. Nine of these were discarded as it was discovered that the glass bottles containing the sample reacted with the calcium ions in the water, taking it out of solution. A counter-experiment was carried out to

test this. Two of these nine glass bottles were filled with water of a known calcium concentration (ppm) and after two months the solution was re-tested for calcium. It was discovered to have decreased by approximately 100 ppm. Of the original 25 samples only 16 proved to be uncontaminated.

The results of these tests show that the total hardness is fairly constant throughout the field season, varying from 515 ppm to 549 ppm for Mound 1; 480 ppm to 548 ppm for Mound 2; and 483 ppm to 521 ppm for Mound 3 (Appendix 3). The mean and standard deviation of calcium, magnesium and total hardness for the three mounds are listed in Table 13 along with the results of Van Everdingen (1973) and Ford (1974). No obvious marked change in calcium or magnesium hardness was noticed throughout the field season but the results do differ from those of Van Everdingen and Ford. Reasons for these large discrepancies are unknown.

Two samples were taken at the base of Mound 1 to show how much calcium and/or magnesium is lost from solution. One sample was taken from flow over the edge of the mound and another from throughflow out of the undercut portion of the mound. Both showed a marked decrease in calcium concentration but little or no change in magnesium. In comparison with a sample taken from the vent at the same time,

they were 197 and 199 ppm less in calcium ions and both were 28 ppm less in magnesium ions. This indicates that it is mainly calcium that is deposited and very little magnesium. This is verified by the chemical analysis of the tufa rock (Table 17).

b. Isotopic analysis of waters: The results suggest that all of the waters are of meteoric origin (Table 14 and Figure 4:10). The spring waters are probably representative of "mean" ground water and are therefore slightly lighter than the environmental waters which are usually isotopically heavier in summer. The spread of results is about that expected for meteoric waters i.e. nothing unusual has happened to these waters (P. Thompson, pers. comm. 1978). Therefore, these waters are not juvenile and have only been in the ground for a relatively short geological time, i.e. in orders between 1 and 100 years.

c. Other geochemical aspects: Some of these were measured in the field; pH, conductivity and dissolved O_2. The trace elements were measured in the laboratory by R.O. Van Everdingen (1973).

The pH was found to be slightly acidic and shows slight temporal variation (Table 15). Ford (1974) recorded a pH of 6.45 and Van Everdingen (1973) one of 6.6. The mean pH found this field

season was 6.42 at the surface.

Specific conductivity was 1030 micromhos per cm at the surface and 1080 micromhos per cm at the bottom of the vent (measured by R. Wickstrom).

Dissolved O_2 was zero at both the surface and the bottom of the vent. This reading is acceptable for the bottom but is incompatible with the algae and animal (crustacean and plankton) life found at the surface. This implies that the algae use CO_2 from the water which would increase the rate of $CaCO_3$ deposition and give off O_2. The crustaceans and plankton must either take their O_2 from these bubbles rising up through the water or come to the surface to breath. Van Everdingen (1973) also found a very low dissolved O_2 reading (0.2 ppm).

Table 16 lists the concentration of the elements found in the water of Mound 1. These measurements were made by Van Everdingen (1973) and Ford (1974), and the author during the field season of 1978. The water contains mainly calcium and bicarbonate ions which have formed by the carbonate ions combining with the water. There is very little sulphate and only traces of sodium, potassium and chloride.

2. White granular precipitate: A soft white precipitate was found on the ground and lower portions of trees and bushes (Plate 3), along the southwestern side of Mound 1

and also on the ground beneath the undercut section of the mound adjacent to the river. On the ground it was laid out in a dendritic pattern as if deposited by small streamlets. It coated the lower trunk of trees up to about 40 cm above the ground and was also found directly beneath fallen trees which were not in contact with the ground; they are held up by other trees which have blocked their fall. At the beginning of July, it was noticed that ice was still present in the areas where it was shaded from the sun. The ice itself was covered in places by the white precipitate. The precipitate feels granular when rubbed between the fingers, is calcareous and reacts with HCl. It is white and is very soft.

An origin has been postulated for this precipitate (E. Hiscock, pers. comm. 1978). Snow accumulates during the winter all around the mound. In the southwestern area of the mound, small streamlets were observed to flow off the mound and under the thin soil cover present. During winter and early spring when the snow is lying in this area these small streamlets will flow into the snow, freeze and form ice. The streamlets will have high concentrations of calcium and possibly magnesium from the hot spring. When the ice melts in early July it leaves behind calcium which has precipitated on the ice.

This hypothesis adequately explains why the precipitate is laid down in a dendritic pattern (because small streamlets flowed into the snow); why it is found

up to 40 cm above the ground on tree trunks; and why it is found directly beneath fallen trees, (because when the snow and ice melt from the trees the drops of water contain calcium which is deposited on the ground beneath the tree trunks, and also on the underside of these trees). In the undercut section of the mound, water falling from above will drip onto the snow and ice and similarly form ice with precipitated calcium in it.

3. Conduits in Mound 1: Small round conduits were observed in the undercut section of Mound 1. The diameter of the conduits varies from less than 1 cm up to 8 cm. They are found between the base of the mound and 2.5 m above (Plate 4).

The author postulates two possible origins for these conduits: (i) they are solutional features; (ii) they are voids left by dead trees and roots which fell into the mound and were coated by $CaCO_3$.

The former hypothesis is based on the fact that the mounds are porous, as water was observed trickling out from the underside of the undercut section. If the water flows through the mound, and the mound is composed of $CaCO_3$, it is feasible that it may flow through "micro cave" systems which it has dissolved. These conduits are round and resemble water-filled passages of cave systems. The argument against this hypothesis is that the water expelling from the vent is saturated with $CaCO_3$, and therefore would pick up more $CaCO_3$ and form

"micro caves".

The second hypothesis is much more acceptable, as a similar process occurs at present on Mound 3 (Plate 5). If a tree falls into the flow from the vent it becomes coated with $CaCO_3$ and forms a vegetation rim (Chapter 6). The vegetation rim increases the surface area of the waters flowing over it and deposition of $CaCO_3$ is accelerated upon it. Eventually the tree decays leaving a void in the tufa.

A three dimensional branching network was observed in these conduits and this resembles branches or roots of a tree. Also bark-like imprints were observed on the walls of a number of these conduits (M. McKeever, pers. comm., 1978).

The fact that these conduits are only found within the first 2.5m of this mound would suggest that initially, when the mound started forming, the area was heavily vegetated and initially the tufa deposition had to compete against the vegetation. A similar process is occurring on Mound 3 at present (Chapter 6). This suggests that Mound 3 is in its early stage of growth.

4. Chemical composition of the tufa: Geochemical analyses were conducted on a sample of tufa from Mound 1 by the method of X-ray diffraction. The results show that the tufa is a very pure crystalline rock containing greater than 99 percent $CaCO_3$. The results are listed in Table 17.

These results imply that most of the other elements listed in the geochemistry of the waters are not deposited on the mound but are transported across and down into the Rabbitkettle River. Only the amounts listed in Table 17 are deposited and are incorporated into the tufa.

5. Spring adjacent to tufa area "b": A small spring was discovered north of tufa area "b" ("Shower Spring"). Its waters contain a high concentration of calcium, between 252 and 264 ppm (Appendix 3), which it deposits on the surface in the form of tufa. Tufa is being deposited along the entire course of the spring, and a tufa platform is presently being built out into the Rabbitkettle River. A cross-section of this platform (Figure 4:11) shows alternate layers of mud rich tufa and pure tufa. The mud rich tufa is formed by fine sediments from the Rabbitkettle River in flood being deposited and later covered by tufa on this platform. When the Rabbitkettle River has low discharge pure tufa is deposited by this spring over the mud-rich tufa. This suggests that the tufa is in competition with the erosive nature of the Rabbitkettle River and is succeeding.

The temperature of this spring water is approximately 12^{0}C. While this temperature is much cooler than the hot springs, it is at least 10^{0}C higher than mean groundwater temperature. This comparatively

warm temperature suggests that the spring may be connected to the hot springs sources but the waters are able to cool before surfacing.

The waters expelling from Mound 2 sink into the ground 32 m northwest of the vent. This point is directly up slope from the Shower Spring. Therefore it is postulated that the waters from Mound 2 flow down slope to approximately the area of tufa area "b" where they are impeded by the tufa dam surrounding this area. Here the groundwater assists in the formation of patterned ground. Eventually, having being stored for some time in this perched watertable and thus cooling down to 12^{0}C, the waters breach the tufa dam and emerge at the spring.

V. CHAPTER 5

PERIGLACIAL ACTION AT RABBITKETTLE HOT SPRINGS

Having a mean annual daily temperature of $-7.8^{0}C$, the Rabbitkettle area lies within the discontinuous permafrost zone, as ascribed by Brown (1970). He states that the discontinuous permafrost is up to 12 m thick at Hay River, N.W.T. ($61^{0}N$) beneath a 1 - 3 m thick active layer. Rabbitkettle, which is at a similar latitude but at a higher elevation, probably has a slightly thicker layer of discontinuous permafrost than at Hay River.

A soil pit was dug in tufa area "b" (Marsh and Scotter's 1976 map) at Rabbitkettle Hot Springs and temperatures of the soil were recorded at various depths. Digging was hindered at a depth of 63.5 cm when fluvial gravels were encountered. These fluvial gravels are probably of deltaic origin similar to those beneath Mound 1 (Ford, 1974). The total depth dug was 1.2 m and the temperature readings are listed in Table 18 and shown in Figure 5:1.

These readings were recorded in mid-July and when plotted on a graph suggest that at approximately 130 cm frozen ground would be encountered. Due to the length of time taken to dig a few centimetres in the river gravels, it was realised that the temperatures of the ground would be raised by exposure to the warm air temperature during digging so the pit was terminated at 120 cm.

Patterned ground

With the presence of discontinuous permafrost in the area it is not surprising that other periglacial features should be found. Among these are patterned ground and frost shattering.

Patterned ground is found in many areas adjacent to and upon the Rabbitkettle Hot Springs mounds. Much literature on patterned ground, its origins and classification is available. One of the more accepted classifications of various active forms of patterned ground was described by Washburn (1956, p 824):

> "Patterned ground is a group term for the more or less symmetrical forms, such as circles, polygons, nets, steps and stripes that are characteristic of, but not necessarily confined to, mantle subject to intensive frost action."

He also divided the classification into sorted and non-sorted varieties of circles, nets, polygons, steps and stripes and put forward 19 different hypotheses of origin. Nicholson's (1976) paper titled "Patterned ground formation and description as suggested by the low arctic and subarctic examples" appears to be the most applicable to the Rabbitkettle patterned ground.

Nicholson (1976) avoids the use of genetic descriptions which might have to be changed as more evidence becomes available and makes field description as simple as possible while maintaining a maximum of useful information. Patterned

ground is recognised when some surface variation marks approximately regular units that are repetitive in form and size. The individual units may be contiguous and regularly arranged or they may be isolated with no regular arrangement. Hence Nicholson uses four criteria which seem most useful for description and these terms may conveniently be used in conjunction with each other, e.g. isolated stone steps; contiguous vegetation elongates (Table 19).

Nicholson (1976) believes that the movement of particles in patterned ground is a result of frost heave, i.e. pressure from freezing of moisture or water in the ground moves the particles. Greater frost heave is caused by ice lenses fed by moisture drawn to the growing ice crystals through capillary-sized pores. Ice crystals grow perpendicularly to the freezing front which implies that movement (heaving pressure) will be perpendicular to this freezing front. If there is an inclined freezing front due to some differentiation which has developed on or beneath the surface (sorting; materials with different thermal properties; variation of moisture distribution, etc.), it will produce a radial pattern of material (Figure 5:2). Coarse material moves in the direction of heat loss and fine material moves away.

Nicholson (1976) also gives evidence for general circulatory movement (Figure 5:3) of some materials in the pattern; especially the fines. The circulatory movements are explained in terms of accepted mechanisms (compressional and

tensional stress relief due to an inclined freezing front) and others not previously accepted. If the radial model for sorting of fines and stones is combined with the circulatory model for movement of fines, the combined model (Figure 5:4) could explain the development of many forms of patterned ground.

At Rabbitkettle Hot Springs there are six areas of patterned ground and each area will be dealt with separately. The locations of these areas are shown in Figure 0:3.

1. Tufa area "a" (Marsh and Scotter, 1976 Map)
2. Tufa area "b"
3. Tufa area "c"
4. Tufa area "d"
5. Tufa area "e"
6. On Mound 2

Tufa area "a"

This area is situated on Mound 2, and is known in Nahanni Park as the "Pit" and is used as a helicopter landing site. The patterned ground here is of two types; stripes and equiforms.

The stripes are situated on inclined ground of 1^0 - 2^0 slope. Their length varies with the longest being 16.8 m with a width of 1.2 m (Plate 6). The centres of the stripes are elevated above the margins which suggests that there is more heave in the centre. They are non-sorted.

Six stripes were recognised here[1] with a mean length of 8.67 m; standard deviation 6.24 m; range 16.8 to 2.9 m; sample size 6 units. The largest stripe is divided into a fork and not all the units are parallel to the inclination of the ground. This would support Nicholson's (1976) theory that stripes follow drainage lines and not dip of the ground surface. The stripes were not vegetated on the crests, but were at the margins. According to Nicholson's (1976) classification these stripes could be classified as relief stripes.

The equiforms of this area are mainly sorted. Most have finer particles in the centre surrounded by larger clasts. In the northern and southern corners of this area (Figure 5:5), however, the equiforms have large clasts surrounded by finer vegetated material.

The patterns which appear in the central portion of this area have little or no vegetation on them which suggests that they are still active. The only vegetation present is between different equiforms. The larger clasts at the edges exhibit frost "thrusting" as they have their long axes aligned perpendicularly to the ground (Plate 7).

The smaller particles in the equiforms are mostly of tufaceous origin; the tufa is easily broken down by frost shattering. The larger particles are usually non-tufaceous (the percentage of granodiorite and quartz monzonite is very

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[1] Pattern size is a very important physical attribute. For quantitative comparison of sites a representative sample of pattern units should be measured.

much greater than shale pyrite). The larger particles are usually well rounded and are derived from the terrace deposits which underly much of this area.

Sixteen samples of the equiforms were measured and the mean, standard deviation and range size were obtained as follows:

mean = 82.00 cm

standard deviation = 31.64 cm

range size = 30 cm to 125 cm

This area appears to be either a very old tufa mound which has been broken down by frost shattering, or part of an ancient flow from Mound 2 which built up a large rimstone pool in this area. Evidence for this can be found on the northwest side of the area where a ridge running the entire length of the mound exists (Figure 5:6). This ridge is an old rim of tufa which has decomposed into a calcareous soil containing abundant clay particles. The ridge acts as an impervious barrier to groundwater which is dammed up in the area to the east and southeast, providing a perched water table. (During wet periods pools of water were seen in the centre of some of the equiforms where the large clasts are situated. This would signify a rise in the perched water table). This moisture provides a basis for freeze/thaw action within the broken down tufa and terrace gravels and results in patterned ground formation.

Two soil pits (S5 and S6 on Figure 5:6) were dug. That on the tufa dam, S5, revealed 1.2 metres of decomposed tufa

while S6 consisted of 15 cm of calcareous soil or decomposed tufa with terrace gravels underneath. The terrace gravels were coated with a calcareous precipitate which suggests leaching downwards of the calcium.

The absence of vegetation on this patterned ground suggests that the area is still active in winter. Colonisation by grasses, mosses and other lower plants in between patterns would be due to the relative inactivity of these intra-pattern areas.

Tufa area "b":

This area is situated northeast of Mound 1, adjacent to the campsite. The patterned ground in this area contains the largest such features in the Rabbitkettle region and form an equiform pattern. The pattern size is as follows (only the diameter of that part of the equiform containing the largest particles was measured, as the boundary between the marginal area of one equiform and another is indistinguishable):

mean = 2.55 m

standard deviation = 0.61 m

range size = 1.8 m to 3.66 m

There are two sub-areas of patterned ground here:

1. Adjacent to the campsite: here only the larger clasts are exposed. The fines along the margins of the equiforms are covered by soil and vegetation. The soil is predominantly decomposed tufa. The large clasts in the centre of the equiforms, which are mainly granodiorite boulders, are covered with lichens. The

vegetation and lichen cover imply that these equiforms are inactive.

2. The main part of tufa area "b": here the equiforms have large boulders in the centre surrounded by fine material. Boulder size in the centre of one of these equiforms was measured (see Appendix 4). The long axes varied from 67 cm to 37 cm with a mean of 50 cm. The boulders were well rounded being predominantly 60 percent of granodiorite.

The intermediate sized particles were between 5.6 cm and 0.3 cm with lithology consisting of 40 percent granodiorite, 30 percent diorite, 20 percent shale pyrite and 10 percent rest. The non-tufaceous material is derived by frost heave from the terrace gravels below.

The finer material was mainly tufa with some non-tufaceous particles, moss and lichens. Particles were of coarse sand size (less than 4 mm long axes) or smaller.

The finer material is colonised by vegetation and some small spruce trees have grown between the larger particles. This suggests that these equiforms are not active.

The reason for patterned ground being present in this area is similar to that in tufa area "a". The area was possibly an ancient tufa mound or an old rimstone pool formed by waters venting from a mound. An old tufa

dam on the boundary of the campsite (Figure 5:7) and the tufa dam still exposed at present to the north, act as impervious layers to ground water and form a perched watertable beneath the patterned ground. Gurgling sounds can be heard when boulders are moved. Similarly freeze/thaw action within this perched water table results in the formation of the equiforms.

Water discharging from the ground (Shower Spring) north of the area may in part come from groundwater in the perched water table. This water is highly mineralized and is depositing tufa on the ground.

Tufa area "c":

This area is situated northeast of Mound 1 and is really a continuum of tufa area "b". However, the equiforms are smaller and are better vegetated. They are non-sorted and the upper layers are composed mainly of tufa. They could be described as vegetated contiguous equiforms.

The pattern diameter is:

mean = 88 cm

standard deviation = 20.43 cm

range size = 55 cm to 110 cm

sample size = 10 units

Moisture needed for patterned ground formation is available from the same perched water table as at tufa area "b".

Tufa area "d":

About 60 percent of the equiforms here have fines in the centre. The material is mainly tufa with about 20

percent of the large material being composed of granodiorite and diorite with minor quantities of quartzite, shale-pyrite and shaley-slate.

The long axes of the large material (listed in Appendix 5) vary from 70 cm to 15 cm, with the non-tufaceous material being well rounded. Hence, they are derived from the terrace gravels beneath (Figure 5:8). Diameter of equiforms are as follows:

mean = 117.6 cm

standard deviation = 58.2 cm

range = 262 cm to 78 cm

sample size = 10 units

The margins of the equiforms are heavily vegetated with some colonisation of the fines in those equiforms with large clasts in their centres. This suggests that the margins are inactive.

Tufa area "e":

This is situated to the west and is an ancient flow area of Mound 2. As with tufa area "b", an old tufa dam provides a perched water table beneath this area. Pools were observed during and immediately after heavy rains. Diameter characteristics of the equiforms are as follows:

mean = 1.20 m

standard deviation = 0.34 m

range = 0.9 m to 1.74 m

sample size = 10 units

The equiforms have mainly large clasts in their centres (listed in Appendix 6) of granodiorite, quartzite, diorite and tufa conglomerate. The size of the large clasts is between 79 cm and 24 cm (long axes). The large clasts were derived by frost heave of the underlying till. Fines are composed entirely of tufa. Also found in tufa area "e" are large boulders (1 - 3 m, "a" axis) which Ford (1974) termed as "ice-rafted".

Equiforms are also found below the tufa dam (very decomposed tufa) to the south east of Mound 1. These are contiguous with the patterned ground east of Mound 1. The lithology of the clasts includes some shale-pyrite and slaty-shales which implies that the clasts are frost heaved up from the terrace gravels, unlike the equiforms above the dam which do not contain clasts of this lithology.

Patterned ground on Mound 2:

Small equiforms and stripes are situated along the entire eastern side of Mound 2 near the junction with Mound 3. Ford (1974) described these as "pretty frost polygons". Their dimensions and particle sizes are very small compared to others previously mentioned. No vegetation exists on these formations except for a few lichens and mosses. This suggests that they are still very active in the winter.

The patterned ground is composed entirely of tufa which has decomposed from the hot spring mounds by frost shatter. Most of the larger particles are flat.

1. Equiforms: The diameters are relatively small:

mean = 40.6 cm

standard deviation = 8 cm

range = 55 cm to 27 cm

sample size = 20

In contrast to the other mound area, there is a gradational sorting from the fines in the centre to large flat particles at the margins. The size of the particles sampled are listed in Appendix 7. About 50 percent of the fines fall within the size range of 1.41 mm to 2.83 mm in diameter. The large particles have a long axis up to 6.9 cm, although a few larger broken slabs of tufa lie around the margins. These can be up to 30 cm long ("a" axis).

To the southeast of Vent 2 the equiforms are white in colour (fines) in the centre with greyish margins (large particles, Plate 8). This indicates that the fines are more active because of less weathering. The flat nature of the larger particles would hinder movement by frost heave to a certain extent and so they are moved less than the fines.

The grains or particles beneath the surface are damp. This moisture provides the basis for frost heave in cold periods.

South and northeast of the vent are more equiforms of similar size to those in the southeast. The difference here is that the sediments are reddish-brown. This is because the tufa involved in the frost heave has

been deposited in more recent times. It was observed that some of the tufa is reddish-brown when freshly deposited, turning orange-brown to dull white as it ages. It then turns grey if it is subjected to effective chemical attack from rainwater and snowmelt. Ford (1974) also observed these properties. This observation of the red-brown colour of the equiform particles provides a clue to the whereabouts of the overflow routes used by the waters expelling from Vent 2.

Traversing from the centre to the margins of these equiforms the larger particles tend to have their long axes aligned perpendicularly to the ground surface (Plate 9). The equiforms to the southeast have the large particles with their long axes parallel to the ground. This implies that the large particles in the red-brown equiforms are more active than those in the southeast. This is also indicated by the fact that the large particles in the northeast and south are less weathered than those in the southeastern equiforms.

2. Stripes: Stripes are found on the inclined ground surface around the fossil vent southeast of Vent 2 and to the east of Vent 2. Again, there is a gradation from fine particles in the centre to coarse along the margins (sizes listed in Appendix 8). The size of the large particles is up to 7.6 cm (long axes) while 68 percent of the fines are between 2.83 mm and 4 mm in diameter. All the particles are derived from broken down tufa

layers and have similar properties (colour and particle alignment) to those of the equiforms southeast of Vent 2. Stripes found to the east of Vent 2, however, are red-brown and the large particles have their long axes perpendicularly to the ground. This is similar to the equiforms northeast of Vent 2.

Length of stripe is controlled by length of inclined ground. Around the fossil vent their length is:

	mean	standard deviation	range	sample
length	1.17 m	0.14 m	1.3-0.95 m	10
width	26 cm	3.94 cm	30 - 20 cm	10

East of vent 2 they are smaller:

	mean	standard deviation	range	sample
length	50 cm	9.62 cm	60 - 38 cm	10
width	11.6 cm	4.3 cm	16 - 10 cm	10

Frost shatter

The effects of frost shatter were observed on all the mounds, especially Mound 1, in the form of exfoliation of the tufa layers (Plate 10). Jennings and Twidale (1971) noted similar exfoliation on granitic rock which they termed as "A" tents (Plate 11 and Figure 5:9). "A" tents were common on the northeast to southeast side of Mound 1.

Frost shatter is a result of moisture, provided from the hot springs, seeping between the tufaceous layers. Freezing in winter causes pressure by the expansion of water

on freezing. This pressure causes the outer tufa layer to crack and eventually break off in slabs. This is not present in the flow area of Mound 1. Another possible genesis for these spalled slabs may be a result of thermal contraction.

"A" tents are a result of lateral compression causing buckling of the outer layer of tufa. This buckling is an expression of the release of this compressive stress. Compressive stress is a result of expansion within the tufa layers caused by freezing of moisture. The point where the stress is relieved is always the apex of the tufa rim.

Frost shatter does not occur on the active parts of Mound 1 because of the warm temperatures of the discharging waters. On the inactive part, however, the moisture collected between layers of tufa does freeze and expand. Frost shatter is the major form of breakdown of the mounds.

Frost heave

Frost heave occurs in the calcareous soils in the relict pools (Plate 12). Freezing of moisture in the voids between particles in the soil causes pressure by expansion of freezing water. This pressure forces the soil particles upwards and forms mounds of soil a few centimetres high.

CONCLUSION

During the winter months the hot springs remain flowing (National Parks staff pers. comm., 1978), and yet patterned ground forms within 10 m of Vent 2 and frost shatter occurs within the same distance of Vent 1. The only apparent explanation for this is that the thermal conductivity of

tufa is very low. In other words, heat from the warm waters in the vents does not penetrate far into the tufa. However, the warm waters do provide moisture for frost action and therefore frost action is accentuated in areas adjacent to the vent, outside an area, with a radius of 10 m from the vent, where heat flow from the waters allows the rock to be heated above 0^oC.

VI. CHAPTER 6

Vegetation Influence upon the Hot Springs Mounds

The deposition of tufa is often associated with plants. At Plitvice, on the River Korana in Yugoslavia, Pevalet (1935) distinguishes four kinds of tufa formed around plant remains, in particular by the lime-secreting action of two plants; the moss (*Bryum pseudotriquetrum*) and the algae (*Cratoneuron commutatum*). The two other tufa types are formed by blue-green algae (*Schizothrix*) and by a grass (*Agrostis*), both in conjunction with the algae. Shelton (1966) also noticed this on the shores of Pyramid, Mono Lakes and the Salton Sea, U.S.A., where tufa is being built up with the help of algae from warm waters rich in dissolved salts.

Therefore, tufa can be formed by three processes which cause the release of CO_2 out of the water when it comes in contact with the atmosphere (which has a lower CO_2 concentration).

1. Turbulence in the water results in diffusion of CO_2 into the atmosphere, for example deposition of tufa at the foot of waterfalls and rapids.
2. Evaporation, for example in hot climates or when pools are very shallow, such as Mound 3.
3. Some plants, such as mosses, blue-green algae and algae, force the extraction of CO_3^{--} from water, while others, such as corals, build up calcite skeletons in the form of tufa. Mosses and algae during daylight hours use CO_2 for photosynthesis. This they can obtain from the highly

mineralized waters of hot springs, such as Rabbitkettle, and hence upset the equilibrium of the water chemistry, resulting in the deposition of tufaceous $CaCO_3$.

Another way in which plants cause the deposition of $CaCO_3$, or tufa, is by increasing the surface area of the water. Mosses and algae, which grow at or near the water surface, increase the surface area of the water and this allows more CO_2 to diffuse into the atmosphere and subsequent deposition of $CaCO_3$.

Therefore, in summary, there are three methods by which plants cause deposition of tufa or $CaCO_3$:

1. By extracting $CaCO_3$ for the building of an exoskeleton
2. Using CO_2 for photosynthesis
3. Increasing surface area of the water.

The latter two occur at Rabbitkettle.

The porous nature of the tufa is caused by the voids formed after the plants decay, and accounts for the density of only 1.3 gm/cc (cf. limestone 2.5 gm/cc). The conduits observed beneath Mound 1 are probably formed in this fashion, by the voids left after the plant has decayed.

At Rabbitkettle vegetation has a profound effect on the build-up of tufa sometimes resulting in unusual structures as seen on Mound 3, (see below).

A. Mound 1

The colonisation of plants on Mound 1 may be divided into two types:

1. Colonisation of the dry tufa areas

2. Colonisation of areas presently permanently covered with water

Vegetation of dry tufa

Two main factors are involved here; aspect and soil formation. Aspect controls the degree of weathering to a certain extent as the southerly facing slopes of the mound are very weathered. Once the tufa is broken down by weathering processes, a fast draining soil-type results thus lack of water is the limiting factor in the growth of vegetation.

The dry weathered pools exist mainly in the northerly sector (Figure 6:1) of the mound as this is the area furthest from the outflow and overspill section. Species found in these pools obtain very little water as the tufa quickly drains off all rain. However, there is some run-off from the edge of the pools into the bottom of the pools where it is retained by the thin soil and organic debris which collect there.

The bottoms of most pools are covered with moss and this often supports a lichen growth on top of it. Some lichens are commonly found existing without the moss in these pools. These plants form about 80 percent of the biomass in the area.

The most abundant higher plants in the area are _Dryas integrifolia_ followed by _Saxiffrage aizoides_ and _tricuspidata_. Other species found are _Dryas drumondii_, _Picea_ spp. seedling, _salix_ spp. 1 and 2, and _Betula papyrifera_

(Figure 6:2). The deeper and thus more sheltered these pools are the greater the depth of soil and the greater the amount of vegetation.

The weathered areas on either side of the flow region support a more varied and greater vegetation cover than the less weathered area previously mentioned. Here the following species are found, approximately in order of abundance:

Dryas Integrifolia
Graminae spp 1
Picea spp
Potentilla fruticosa
Arctostaphylos rubra
Arctostaphylos uva-ursi
Pingucula vulgaris
Salix spp 1
Salix spp 2
Rhodendron lapponicum
Betula glandulosa
Sedum spp
Larix Larcina
White Anemone?
Spp A

Several Larch (_Larix larcina_) trees were growing on the mounds, forming a band at approximately the same elevation. These are the only sizeable trees on Mound 1.

In the white unweathered area of Mound 1 very little vegetation grew, only _Dryas integrifolia_ and _Salix_ spp. 1

and 2. These plants were found growing at the edges of pools as nothing grew in the centre due to the lack of soil.

This area was water covered in 1974 (Scotter and Marsh, 1976) and may have been wet since then. Probably the plants growing around the edges were established when it was wet. The first plant observed to colonise the centre of the pools is *Dryas integrifolia*.

Vegetation of the wet area (flow area)

This was very restricted, with some small salix spp. and moss in small pools. At the outlet on Mound 1 a moss has formed a calcareous vegetation mound. The rim of this mound rises above the central area thus protecting the *Dryas integrifolia* from flooding by the outflow. Also in this depression are two salix spp. The mound is 50 cm in diameter (Figure 6:3). In the outflow from the vent, algae (species unknown) is found in abundance. This algal species is brownish in colour and consista of long mats of filament. The algae provides a base for the precipitation of $CaCO_3$ or tufa by the processes mentioned above. Some partially calcified algae were observed which supports this hypothesis. Plate 13 shows the partially calcified algae beside vent 2. It has been noticed on many occasions (Black, 1970) that several different types of algae, collectively referred to as the calcareous algae, secrete $CaCO_3$ and are readily preserved.

Vegetation of Mound 3 (with special reference to the effect of vegetation on the morphology of the mounds

The outflow from Vent 3 is irregular and the area around it is quite level. Water stands in shallow pools containing tufaceous mounds supporting vegetation. It appears that these mounds or islands (Plate 14) are of two origins:

1. Areas which are naturally higher than the surrounding tufa and are not flooded. These are characterised by irregularly shaped sloping edges and flat tops.
2. The origin of the second type of vegetational mound or "island" is shown in the diagrams of Figure 6:4. The first diagram shows moss shoots growing almost submerged in about 5 mm of water. At this stage the moss is a red colour and survives readily in this aqueous environment. Diagram (ii) shows a rounded mound of moss which provides a large surface area onto which the calcium can precipitate. Extraction of CO_2 by the moss may enhance calcium deposition. Once the moss has grown above the water it becomes green. The third diagram shows the same mound after a period of time during which the tufa has risen from level 1 to 2 outside the mound and a concave tufaceous mound has formed with its lowest point the initial level of the water. Diagram iv shows a later stage when, for some reason, the moss forms a convex lid on the mound under which lies organic debris from the previous generations of moss. Diagram v represents an even later stage when the calcified rim has grown higher and outwards.

In stages (iv) and (v) the mound is colonised by higher plants because the moss and the organic debris it has formed provide anchorage for the roots and a base for nutrients.

The vegetation mounds are greater than 4 cm in diameter. Those in a wetter environment are first colonised by *Pinguicula vulgaris*, while mounds in drier areas are colonised by *Dryas integrifolia*, *spp.* A, *Parnassia spp*, *Lobelia kalmii* and *Picea glauca* (approximate order of importance).

Table 20 and Map 2 show how the islands are colonised. The first plant to establish itself after the moss is usually *Dryas integrifolia* although on some of the wetter, very small mounds *Pinguicula vulgaris* may establish first (islands 23, 61). Colonisation by higher plants occurs when the islands are between 4 - 13 cm in diameter.

These islands are characterised by their roundness and hollow centres. Island 6 is an example of a mature mound, probably a conglomeration of various islands. Its centre is 40 cm deeper than the present water level. A *Picea glauca* plant growing in the centre of this island provides a minimum age for the initiation of the vegetation mound. Members of the Parks Canada staff placed the age of this tree between 75 and 150 years. A growth rate for calcium carbonate or tufa forming a dam 40 cm high in this time span is indeed very fast (2.67 mm/year). This would support Ford

(1974) who gave an age of less than 10,000 years for the mounds of the Rabbitkettle Hot Springs (for Mound 1, 2.54 mm/year).

Island 15 is a typical, less mature mound at stage (iv) of Figure 6:4. It is 18 cm in diameter while the top of its vegetation cover is 6 cm above water which is 2 cm deep. The height of the tufa rim is 2.5 cm and the depth of the hollow in the centre is 6 cm. This shows that the build-up of the rim is very fast compared with that of the surrounding tufa and that vegetation, especially mosses, enhance the deposition of $CaCO_3$.

A third type of calcareous mound occurs on the dry tufa (Figure 6:5) but was not identified in the wet areas. This type of mound is almost conical in shape, has a hole in the centre and has the appearance of a miniature volcano or nippleoid topography (Plate 15). The origin of these appears to be the advance of water onto an area supporting trees which consequently die as their roots drown. (This could be seen as there were dead trees present in places recently flooded). The next stage would be the colonisation of the dead tree trunk by mosses and other plants. These would be coated with calcite or tufa and the mound would grow upwards and outwards as the water level rose or fell. The steepness of the mound would depend on the speed of this rise or fall; the faster the rise or fall of water, the steeper the mound. The final stage is when the dead tree eventually rots away, leaving a hole in the centre of the tufa. The moss will die

as its food store has gone and all that remains is a nippleoid tufa mound.

On the mounds immediately surrounding Vent 3 there was a different order of succession after the moss was established and *Juncus arcticus* became dominant (Plate 16). This plant prefers a wet meadow environment and therefore the area adjacent to the vent would be most suitable.

The first two types of mounds are found in fossil form to the south (Map 1). This area is now inactive and mostly bare of vegetation except for a few *Betula glandulosa*. The reason for this is that the flow from Vent 3 changed to its present position in the recent past and so cut off the water supply to the plants in this area to the south. The only plants that remain are the *Betula glandulosa* which can tolerate periods of little water and colonise the fossil vegetational mounds where there is a thin veneer of soil.

Plants found in this area must adapt to a very unusual environment. Some, such as pinguicula vulgaris, are insectivorous and catch insects for their source of nitrogen, which is lacking in the hot springs' water. Others such as *Juniperus horizontalis*, which creeps across the tufa surface, must be able to withstand being covered by water and then coated with deposited calcium carbonate (Plate 17). Many of these plants were seen to have withstood this and continued living.

The identification of the plants was carried out rather haphazardly as no complete floral references were available.

Lower plants such as the bryophyta and algae were not identified. Therefore many species listed in Table 21 are incomplete and open to correction.

VII. CHAPTER 7

CONCLUSION

It is certain that the Rabbitkettle Hot Springs are very active at present, both hydrologically and physically. The waters venting from the three mounds are saturated with calcium and magnesium which explains the fast build-up of the tufa. An age of less than 10,000 years has been ascribed to Mound 1, based on its superposition upon terrace gravels deposited in deltaic facies of the meltwater streams associated with the Hole-in-the-Wall Glaciation (Classical Wisconsin).

Ford (1974) stated that given an age of less than 10,000 years the north mound is growing at roughly 0.1 inches (2.54 mm) a year. A similar growth rate was estimated for Mound 3, where a vegetational tufa dam had grown to a height of 40 cm surrounding a spruce tree (Picea glauca) of between 75 and 150 years of age. Allowing for the maximum age of 150 years, then the calcium has precipitated at approximately 40 cm/150 years or 2.67 mm/year. This estimate may be reduced slightly as vegetation enhances tufa precipitation.

Mounds 2 and 3 are much younger than Mound 1. This is based on the assumption that all three mounds are connected hydrologically to the same aquifer because the chemical and physical aspects of the waters are almost identical. Also, when discharge increases in Mound 1 it increases simultaneously in Mound 2. Therefore, it is postulated that

all three are connected. Mound 1, the base of which is much lower than the others, would take all the waters until the tufa had been deposited to a height level with the glacial till upon which Mounds 2 and 3 are deposited. Then Mounds 2 and 3 would begin forming as the waters discharged from the newly formed vents.

Although the mounds grow at a fast rate they are also subjected to much breakdown, mainly by frost shatter. The very existence of the mounds proves that build-up exceeds breakdown rates. However, tufa areas "a" and "b" may be former mounds where breakdown exceeded growth, or where growth ceased and frost shatter took over.

Frost shatter, in the form of exfoliation or spalling and thermal expansion, has a very visible effect on the mounds. Spalled layers of tufa are observed in great quantity around the periphery and on Mound 1. Forms of "A" tents are also present on Mound 1.

Various chemical aspects were measured and little or no temporal variations existed throughout the field season. Temperature of the hot spring waters remained constant with time and depth, (Mound 1 was 21.5^{0}C; Mound 2, 21^{0}C; and Mound 3, 20.6^{0}C). Calcium hardness was similar for all three mounds; between 375 ppm for Mound 1 and 404 ppm for Mound 3. Magnesium hardness varied slightly; the lowest reading being 83 ppm for Mound 3 and the highest 208 ppm for Mound 1.

The isotopic composition of the waters suggests that the waters are of meteoric origin. The distribution of

results probably represent "mean" groundwater. Therefore these waters are not juvenile.

The pH of the waters indicated their very slightly acidic nature. This is not surprising as the dissolved CO_2 content is high (91 ppm) which accounts for the acidic pH (6.4).

A chemical analysis of the spring deposit, or tufa, by the X-ray diffraction method, showed that the tufa is a very pure crystalline rock containing greater than 99 percent Ca. This implies that most of the other elements found in the geochemical analyses of the water, including magnesium, are not precipitated out but transported with the waters into the Rabbitkettle River.

In the physiographic analyses of the mounds it was observed that there is a relationship between the width of the rimstone and the slope of the mound. As the pool width becomes larger the slope of the mounds decreases. A linear relationship exists between pool width and height of the outside of the rim. In the upper portion of the mound it has a low positive relationship, $Y = 4.31+0.15X$, while in the lower portion it has a high positive relationship, $Y = 0.3+0.96X$. Another physiographic relationship discovered was that the thickness of the tufa layer decreased with an increase of slope angle on the outside of a tufa rim. Curtain forms in the tufa began developing when the angle was 90^0 or greater.

Two features were observed to have unusual association

with the mounds; namely periglacial influence and vegetational influence.

1. Patterned ground in the form of stripes and equiforms was observed on Mound 2 and in the areas of broken down tufa adjacent to the springs. Frost shatter initially breaks down the tufa and then freeze-thaw cycles sort the particles into patterned ground. Nicholson's (1976) hypothesis for the origin of patterned ground appeared to be applicable to the Rabbitkettle phenomena, as it explains the origin of both types of equiforms at Rabbitkettle; those with fine material in the centre and those with large particles in the centre.

   The interesting factor involved in the patterned ground formation is that the hot springs which remain at constant temperature throughout the year have no thermal influence on the patterned ground forming more than 10m from Vent 2. This is attributed to the fact that the thermal conductivity of the tufa is not high enough to keep the temperature of the rock, in the areas where patterned ground is forming, above 0^{0}C. The hot springs do provide moisture throughout the freeze-thaw season for the frost movement of the particles in the patterned ground. The patterned ground on Mound 2 is still very active and is also very sensitive to trampling.

2. Vegetation growth has a profound effect on the morphology and formation of the mounds. Algae growth in the main outflow of the three mounds aids the

precipitation of tufa. Algae masses in the flow are photosynthetic and absorb CO_2 from the waters which upsets the chemical equilibrium of the waters and causes $CaCO_3$ to be deposited in order to maintain this equilibrium. On the third mound unusual calcified vegetation hillocks or mounds, about 10cm high and 15cm in diameter, have formed. Three distinguishable forms of these vegetational mounds have been identified. In each case moss is the main base upon which the calcium precipitates and the moss also increases the precipitation by extracting CO_2 from the water, by photosynthesis and by increasing the surface area of the water thereby allowing more diffusion of CO_2 from the water. Once the moss has formed a tufa base upon which humus and other organics form colonisation by higher plants occurs. The process of colonisation of these mounds was examined. Colonisation by higher plants such as gymnosperms gives an insight into the rate of deposition of the tufa.

Much work still needs to be undertaken upon the various scientific aspects of the Rabbitkettle Hot Springs. A more detailed history of past glacial and fluvial events; long term monitoring of discharge, temperature and geochemistry of the hot springs; the installation of micro-erosion meters upon the mounds will give a more exact figure for deposition of the tufa; and tritium analysis of the hot spring waters may show if the water venting at the mounds is pre-1954 or

not (the year a sharp increase in atmospheric tritium levels occurred). As the above data were not available at the time the research was done it must be realised that this work is preliminary.

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TABLE 1.

Correlation of glacial events in South Nahanni Park, (after Ford 1976).

	Laurentide glacial zone	Central non-glacial zone	Cordilleran glacial zone
Postglacial 'classical' Wisconsin	→ Jackfish Glaciation and ← Glacial Lake Tetcela →	Second Virginia Falls	Hole-in-the-wall Glaciation
'early'			
Sangamonian Interglacial ≤145,000 B.P.			
Illinoian	→ Clausen Glaciation and ← Glacial Lake Nahanni →		← Flat River Glaciation
190,000 - 220,000 B.P.		Grotte Valarie Interglacial II	First Virginia Falls
275,000 - (350)320,000 B.P.		Grotte Valerie Interglacial I	
≥350,000 B.P.	First Canyon Glaciation →	?	← - - - - - - - - valley glaciation Penecontemporaneous ?

Table 2

Mean daily temperatures for the Rabbitkettle locality as estimated by Burns (1973)

Annual	January	April	July	October
	Mean daily maximum temperature (deg C)			
-2.5	-15.0	-1.1	18.3	-3.0
	Mean daily temperature (deg C)			
-7.8	-22.0	-8.0	10.8	-8.0
	Mean daily minimum temperature (deg C)			
-15.0	-26.1	-13.6	4.4	-12.8

Table 3

Precipitation in amount and occurrence at Rabbitkettle and Fort Simpson localities (Burns 1973).

	Annual	January	April	July	Oct
	Mean precipitation, cm of water				
Rabbitkettle	76.0	5.1	3.8	8.9	6.3
Virginia Falls	71.0	4.4	3.2	8.3	5.7
Fort Simpson	38.2	2.5	1.9	6.3	3.8
	Mean number of days with measurable precipitation				
Rabbitkettle	230	18	14	20	20
Virginia Falls	205	18	12	18	18
Fort Simpson	120	12	8	10	10

	Mean number of days with measurable		Mean Rainfall (cm)	Mean Snowfall (cm)
	Rainfall	Snowfall		
Rabbitkettle	75	155	42	340
Virginia Falls	70	135	40	310
Fort Simpson	50	70	24	142

Table 4

Percent frequency and cover of shrubs, herbs and ground cover in grass vegetation. (Marsh and Scotter, 1976).

Species	Percent frequency	Percent cover
Arctostaphylos uva-ursi	25	10
Artemisia frigida	100	8
		--
		18
Calamagrostis purpurascens	60	3
Elymus innovatus	85	8
Poa glauca	25	T*
Arabis retrofracta	10	T
Potentilla pensylvanica	40	1
Astragalus striatus	50	4
Oxytropis varians	60	6
Solidago decumbens	5	T
		--
		22
Bryophytes	35	1
Lichens	35	4
Litter	100	62
Bare ground	100	29
Rock	35	4

* Trace

Table 5

Percent frequency and cover of shrubs, herbs and ground cover in Black spruce - Labrador tea community. (Marsh and Scotter, 1976)

Species	Percent frequency	Percent cover
Salix glauca	40	1
S. myrtillifolia	80	2
S. cfr. planifolia	5	T*
Betula glandulosa	10	T
Potentilla fruticosa	100	5
Empetrum nigrum	5	2
Shepherdia canadensis	5	T
Andromeda polifolia	30	1
Arctostaphylos rubra	65	11
A. uva-ursi	10	1
Ledum groenlandicum	95	7
Rhododendron lapponicum	5	T
Vaccinium uliginosum	25	1
V. vitis-idaea v. minus	90	16
Linnaea borealis	65	3
		--
		50
Equisetum scirpoides	95	1
Selaginella selaginoides	20	T
Festuca altaica	70	1
Trisetum spicatum	30	1
Carex cfr. aquatilis	15	T
C. concinna	60	2
C. cfr. vaginata	70	2
Geocaulon lividum	35	1
Anemone parviflora	50	1
Gentiana propinqua	5	T
Pedicularis labradorica	5	T
Senecio cfr. indecorus	10	T
		--
		9
Bryophytes	95	19
Lichens	100	45
Litter	100	36

* Trace

Table 6

Percent frequency and cover of shrubs, herbs and ground cover in White spruce community. (Marsh and Scotter, 1976)

Species	Percent frequency	Percent cover
Alnus crispa	5	1
Shepherdia canadensis	5	T*
Vaccinium vitis-idaea v. minus	15	T
Linnaea borealis	25	1
		--
		2
Carex concinna	35	T
Habenaria sp.	10	T
Geocaulon lividum	5	T
Pyrola asarifolia	5	T
P. secunda	20	T
Bryophytes	100	79
Lichens	100	5
Litter	80	18

* Trace

Table 7

Percent Frequency and Cover of Shrubs, Herbs and Ground Cover in White Spruce - Black Spruce community. (Marsh and Scotter, 1976)

Species	Percent frequency	Percent cover
Salix cfr. pseudomonticola	5	1
Potentilla fructicosa	5	T*
Rosa acicularis	15	T
Sheperdia canadensis	50	1
Arctostaphylos rubra	5	T
Vaccinium vitis-idaea v. minus	10	T
Linnaea borealis	15	T
		--
		2
Carex concinna	65	1
Geocaulon lividum	10	1
Lupinus arcticus	5	T
Pyrola asarifolia	35	T
P. secunda	15	1
		--
		3
Bryophytes	100	64
Lichens	100	13
Litter	70	21
Rock	20	2

* Trace

Table 8

Temperatures of Hot Spring waters

Date	Time	Air T (^{0}C)	Mound 1 (^{0}C)	Mound 2 (^{0}C)	Mound 3 (^{0}C)	Spring (^{0}C)
5.7.78	13:45	24.0	21.0			
5.7.78	14:00	24.0		20.5[5]		
5.7.78	14:15	24.0			19.5[8]	
7.7.78	14:13	21.6[1]	21.6[2]			
			21.8[3]			
			21.6[4]			
	14:30	21.6		21.3[5]		
				21.2[6]		
				21.2[7]		
	14:45	21.6			21.7[9]	
17.7.78	14:30	17.4	21.4[1]			
			21.6[2]			
	14:50	18.8		20.8[5]		
	15:15	16.9			21.0[8]	
					20.4[9]	
	15:45	16.9				11.8
19.7.78	12:20	23.0	21.5[1]			
			21.7[2]			
	13:10	24.0		21.0[5]		
				21.0[2]		
	13:40	24.0			20.8	

Sampling positions in vents:

1=South end of vent (shade)
2=North end of vent (shade)
3=in outlet (sun)
4=in outlet at orifice (shade)
5=N.E. end near outlet (shade)
6=S.W. end (shade)
7=S.E. end (shade)
8=S.W. end (shade)
9=N.E. end near upwelling of water

Table 8 (cont.)

Temperatures of Hot Spring waters

Date	Time	Air T (^{0}C)	Vent 1 (^{0}C)	Vent 2 (^{0}C)	Vent 3 (^{0}C)	Spring (^{0}C)
26.7.78	19:00	21.7	21.4^{1}			
			21.1^{2}			
	18:15	20.7		20.9		
				20.8		
	18:00	20.7			20.3^{9}	
					20.9^{8}	
	17:20	20.0				11.7
2.8.78	13:40	29.0	21.7^{1}			
			21.7^{2}			
	14:00	29.6		21.4^{5}		
				21.5^{6}	21.5^{9}	
	14:20	26.9			21.6^{8}	
7.8.78	14:20	24.0	21.6^{1}			
			21.5^{2}			
	15:30	21.5		20.7^{5}		
				20.7^{6}		
	15:40	21.5			20.4^{8}	
					20.4^{8}	
	14:10					12.1
11.7.78	19.00	18.1	21.5^{1}			
			21.4			
	18:00	16.0		20.8^{5}		
				20.8^{6}		
	17:50	16.0			20.6^{8}	
					20.4^{9}	

Sampling positions in vents:
1=South end of vent (shade) 2=North end of vent (shade)
3=in outlet (sun) 4=in outlet at orifice (shade)
5=N.E. end near outlet (shade) 6=S.W. end (shade)
7=S.E. end (shade) 8=S.W. end (shade)
9=N.E. end near upwelling of water

Table 9

Temperatures at varying depth in the vent of Mound 1 (measured by R. Wickstrom).

Depth (m)	T (degree C)
0	21.3
1	21.2
2	21.2
3	21.2
4	21.2
5	21.2
6	21.2
7	21.2
8	21.2
9	21.2
10	21.2
11	21.2
12	21.2
13	21.2
14	21.2
14.7 (bottom)	21.2

Table 10

Descriptive Temperature Statistics for Mounds 1, 2 and 3.

	mean (^{0}C)	standard deviation (^{0}C)	variance (^{0}C)	range*	sample
Mound 1	21.5	0.2	0.04	21.0-21.6	17
Mound 2	21.0	0.3	0.08	20.5-21.5	16
Mound 3	20.6	0.6	0.3	19.5-21.7	14

*shade temperature

Table 11

Discharge from two Hot Springs Mounds (in m^3/sec)

Day	Mound 1	Mound 2
July 21	0.03 cumecs	0.01 cumecs
July 25	0.04 cumecs	0.02 cumecs
Aug 11	0.06 cumecs	0.03 cumecs
Aug 12	0.06 cumecs	0.03 cumecs
Aug 15	0.07 cumecs	0.03 cumecs
Aug 21	0.07 cumecs	0.03 cumecs

Table 12

Thickness of tufa layers with respect to slope angle of rim.

	Distance from top of rim(cm)		rim slope (degrees)	Thickness of tufa (cm)
1	0		0	76
	13		45	61
	25		65	36
	38		74	30
	50		78	21
	64		80	30
	76		85	15
	89	curtains	90	14
	102	formed	95	9
2	0		0	61
	13	curtains	90	48
	25	formed	95	36
3	0		0	198
	13		78	140
	25		81	112
	38		90	64
	50		98	48
	64	curtains	103	42
	76	formed	104	24
	89		105	3
4	0		0	152
	13		90	125
	25		94	67
	38	curtains	100	52
	50		100	15
	64	formed	101	24
	76		100	21
5	0		0	91
	13		69	76
	25		81	70
	38		84	54

Table 12 (cont.)

Sample	Distance from rim top (cm)		Slope angle	Thickness (mm)
6	0		0	76
	13		79	64
	25		92	42
	38	curtains	94	34
	50	formed	96	30
	64		97	27

Table 13

The hardness of the Rabbitkettle Hot Spring water.

	mean (x)			standard deviation			Van Everdingen	Ford (1974)
Mound	1	2	3	1	2	3	1	1
Calcium Hardness	374	389	403	22.03	5.73	10.16	218	530
Magnesium Hardness	155	119	98	35.23	32.32	9.28	337	375
Total	529	507	502	13.2	28.59	13.83	251	905

Table 14

Isotopic analyses of waters from Rabbitkettle Hot Springs and Wild Mnt. Springs.

Sample I.D.	Description	D vs SMOW	018 vs SMOW
Rabbitkettle Hot Springs:			
RKE-1	Environmental water	-172+0.4	-23.6+0.16
W1(d)	Spring water, Mound 1	-180+0.3	-24.1+0.04
W2(d)	Spring water, Mound 2	-180+0.5	-24.2+0.07
W3(d)	Spring water, Mound 3	-180+0.8	-23.7+0.15
W1(f)	Spring water, Mound 1	-180+0.6	-24.2+0.09
Wild Mtn. Hot Springs:			
WM 1	Environmental water	-171+0.5	-22.9+0.13
WM 2	Spring water	-178+0.4	-23.6+0.08

N.B. Hydrogen isotopic compositions were measured by reacting 20 microlites of water with uranium at 750°C.
Oxygen isotopic compositions were measured by equilibrating CO_2 with ml of water at 25.2°C. The fractionation factor between CO_2 and H_2O a this temperature is 1.0412.

Table 15

pH of Hot Spring waters.

Mound	1	2	3	Spring	River
17 July	6.7	6.65	6.65	-	
26 July	6.5	6.6	6.5		
1 Aug	6.4	6.65	6.5		
5 Aug	6.0*				
5 Aug	7.2 at bottom				
8 Aug	6.5	6.6	6.6	7.8	7.7

*measured with pH paper. The higher pH sample was taken from water from the bottom of the vent.

Table 16

Chemical composition of waters from Mound 1.

	Van Everdingen	Ford	Author
Conductivity (micromhos/cm)	1100		1030*
pH	6.6	6.45	6.42
Dissolved O_2	0.2		0
Dissolved CO_2		91 ppm	
Ca	218 ppm	530 ppm	374 ppm
Mg	33.7 ppm	375 ppm	155 ppm
Sr			
Na	4.2 ppm		
K	4.9 ppm		
Li			
Fe	0.12 ppm		
Mn	0.01 ppm		
Cu	<0.001 ppm		
Pb	<0.005 ppm		
Zn	0.009 ppm		
HCO_3	802.1 ppm		
CO_3			
SO_4	3 ppm		
Cl	0.7 ppm		
F	<0.01 ppm		
PO_4			
SiO_2	13 ppm		

Table 17

Chemical composition of the tufa in Mound 1.

$CaCO_3$	>99%
Fe	0.034%
Cu	0.004%
Zn	0.012%
Pb	0.008%
Mg	0.14%
Sr	0.031%
Others	<0.05%

Table 18

Temperatures recorded at varying depths in soil pit in tufa area "b"

Depth (cm)	Temp (^{0}C)
0	19
30	11
60	5
100	3
120	1.5

Table 19

System of patterned ground description (Nicholson, 1976).

Description of form	equiform elongate stripe step other
Description of grouping	isolated semigrouped contiguous
Description of pattern marking	(variations of) relief (variations of) stone (variations of) vegetation (other variations)
Pattern unit size	

NOTE: Equiform - patterns with a surface form that is equidimensional in several directions.
Elongate - Patterns with marked elongation of the pattern unit, but not indefinite elongation.
Stripes - linear patterns without any interruption of the linear form excepting those interruptions which are not an essential part of the repetitive pattern.
Steps - forms on a slope where an area of ground less steep than the general slope is bounded downslope by a margin notably steeper than the general slope.

Table 20

Plant colonisation of vegetation mounds

Island number*	Diameter size	Species colonising
49	2.5	7, 9, 22
61	5	7, 22
62	7.6	7
24	7.6	7
45	7.6	7, 12
48	10	7, 9
9	12.7	7, 10, 12, 13
67	12.7	7
16	12.7	7, 12
10	15.2	7, 12
13	15.2	7, 10
69	17.8	7, 12, 23
15	17.8	1, 7, 9, 10, 19
17	20.3	7, 12
20	20.3	7, 12, 23
47	22.9	7, 12
46	25.4	1, 2, 7, 9, 12, 22
8	30.5	7, 8, 12
66	30.5	7, 12
11	30.5	2, 7
18	30.5	7, 9, 12, 16, 20
19	30.5	7, 9, 12, 16, 20
68	33	1, 7, 9, 12
25	38	7, 8, 9, 10, 12, 19
7	38	2, 5, 10, 14
70	45.7	1, 7, 8, 9, 10, 12, 19, 20, 23, 25
14	53.3	3, 5, 7, 10, 17, 22
23	30.5	7, 10, 13

* The islands numbered are referred to on Map 2.
** Species numbered

1. Picea spp.
2. Betula gladulosa
3. Juniperus horizontalis
4. Linnaea borealis
5. Galium boreale
6. Epilobium angusttifolium
7. Moss spp.

13. Pyrola spp.
14. Spp. C.
15. Arctostaphylos ura-ursi
16. Parnassia spp.
17. Rosa axcularis
18. Salix spp.
19. Lobelia kalmii

8. Potentilla fruticosa
9. Spp. A
10. Graminae spp. 1
11. Bare ground
12. Dryas integrifolia

20. Senecio spp.
21. Orchideae spp.
22. Pingucula vulgaris
23. Spp. B.
24. Cornus stoliniferus
25. Juncus arcticus

Table 21

Species Identified on the Rabbitkettle Hot Spring Cone

Species	Cody & Brigham (1972)	The Authors (1978)	Mound
Polypodiacdae-Cystopteris fragilis	+		?
Pinaceae -			
Juniperus horizontalis(Moench)	+	+	1&2
Juniperus communis(L.S.lat)		+	1&2
Larix laricina(DuRoi) K.Koch		+	1&2
Picea glauca (Moench) voss.s.lat.	+	+	1&2
Picea mariana (Mill) Bs.P.		+	2
Cyperaceae -			
Carex capillaris	+		?
Carex eburnea	+		?
Carex glacialis	+		?
Carex scirpoidea	+		?
Scirpus caespitosus	+		?
Liliaceae -			
Tofieldia Pusilla	+	+	1&2
Zygdenus elegans pursh		+	1&2
Tofieldia coccinea		+	1&2
Orchidaceae -			
Cypripedium calceolus var paxviflorum	+	+	1&2
Cypripedium guctatum		+	1&2
Cypripedium montanum		+	2
Salicaceae -			
Populus balsamifera	+	+	1&2
Salix arbusculoideo	+		
Salix longistylis	+		
Salix longistylis	+		
Salix spp1 1		+	1&2
Salix spp2		+	1&2
Salix spp3		+	2
Betulaceae -			
Betula glandulosa	+	+	1&2
Caryophyllaceae -			
Arenaria dawsonensis	+		
Saxifragaceae -			
Saxifraga aizoides	+	+	1&2
Saxifraga tricuspidata	+	+	1
Parnassia spp		+	1&2
Rosaceae -			
Dryas integrifolia (vahl)	+	+	1&2
Dryas drummondii (Richards)		+	1&2
Potentilla fruticosa L.	+	+	1&2

Rosa asicularis		+	1&2
Amelanchier striatus		+	2
Leguminosae -			
Hedysarum alpenum var. americum	+	+	1
Ericaceae -			
Arctostaphylos rubra (Rohd&Wils) fern	+	+	1&2
Arctostaphylos uva-ursi (L) Spreng	+	+	1&2
Ledum groenlandicum Oed		+	2
Rhodedendron lapponicum L.Wahl	+	+	1&2
Vaccinium uligenosum	+		
Vaccinium vitis-idaea		+	2
Lentibulariaceae -			
Pinguicula vulgaris	+	+	1&2
Compositae -			
Artennaria pulcherrimei	+	+	1&2
Solidago spp		+	1&2
Senecio spp		+	
purple daisy 1		+	
purple daisy 2		+	
Gentanaceae -			
Gentiana propinqua Richards s.lat.		+	2
Santalaceae -			
Geocaula lividum (Richards) fern		+	2
Eleagnaceae -			
Sheperdia canadensis (L) Nult.		+	1&2
Cornaceae -			
Cornus canadensis (L) Gray		+	2
Cornus stolognifera Mich x		+	2
Pyrolaceae -			
Pyrol spp		+	
Rubiaceae -			
Galium boreale		+	2
Capriolaceae -			
Lineae borealis L.		+	2
Viburnum edule (Mich x) Ref		+	
Lobeliaceae -			
Lobelia Kalmii		+	2
Graminae -			
spp 1		+	1&2
spp 2		+	1&2
Epilobium			
Epilobium angustifolium L.		+	2
Unidentified species			
White anenome+		+	1&2
sedum spp lanceolatum Torr.		+	1&2
plant with red berries with black stripes		+	2

Footnote

* 1 & 2 - 1 stands for mound 1, and 2 stands for mounds 2 & 3 together because boundary between the two is unidentifiable.

1 These salix spp. unidentified by author maybe those listed by Cody and Brigham (1972).

+ These are local names - scientific names unknown.

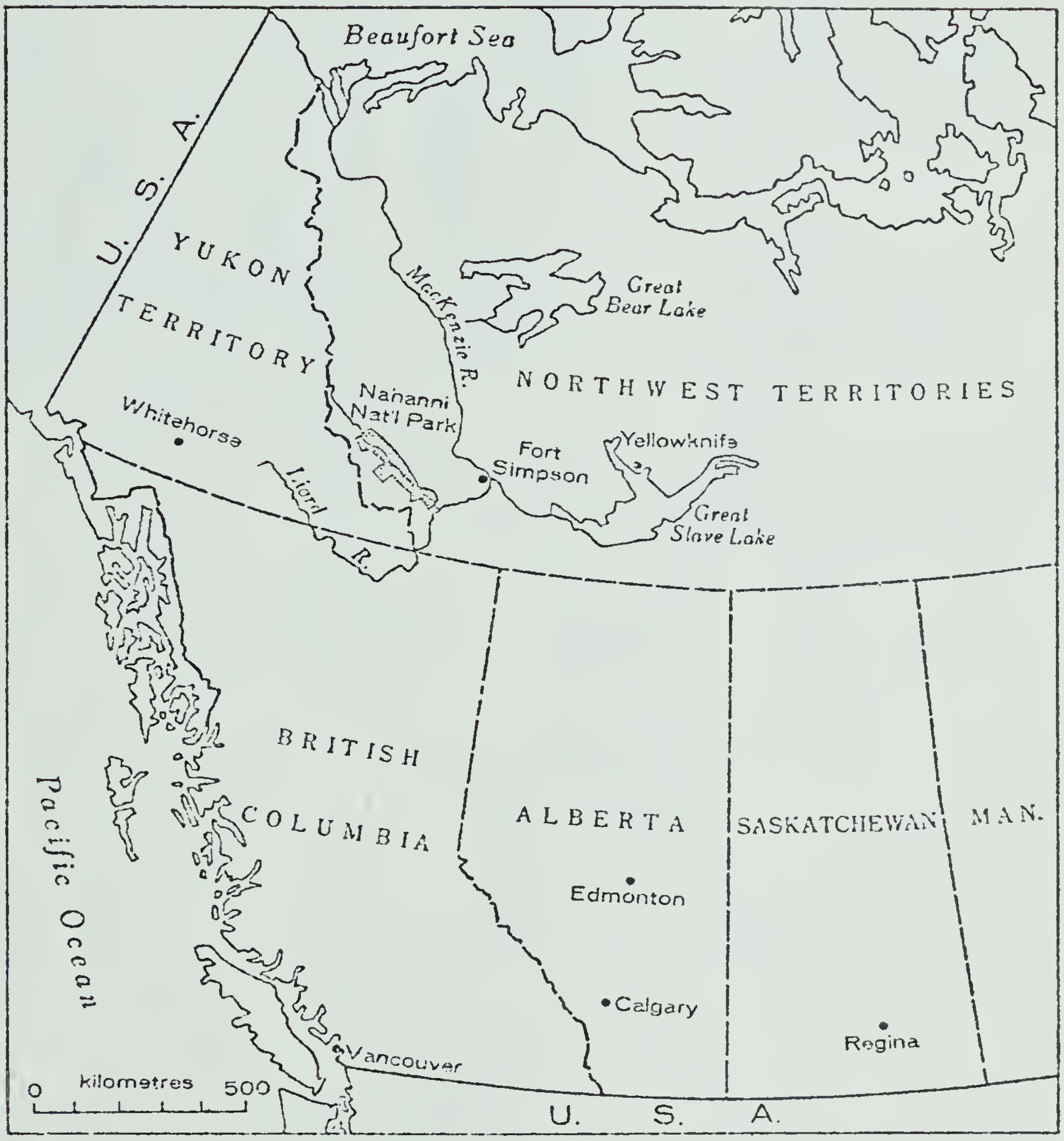


Fig. 0:1 Map of Western Canada

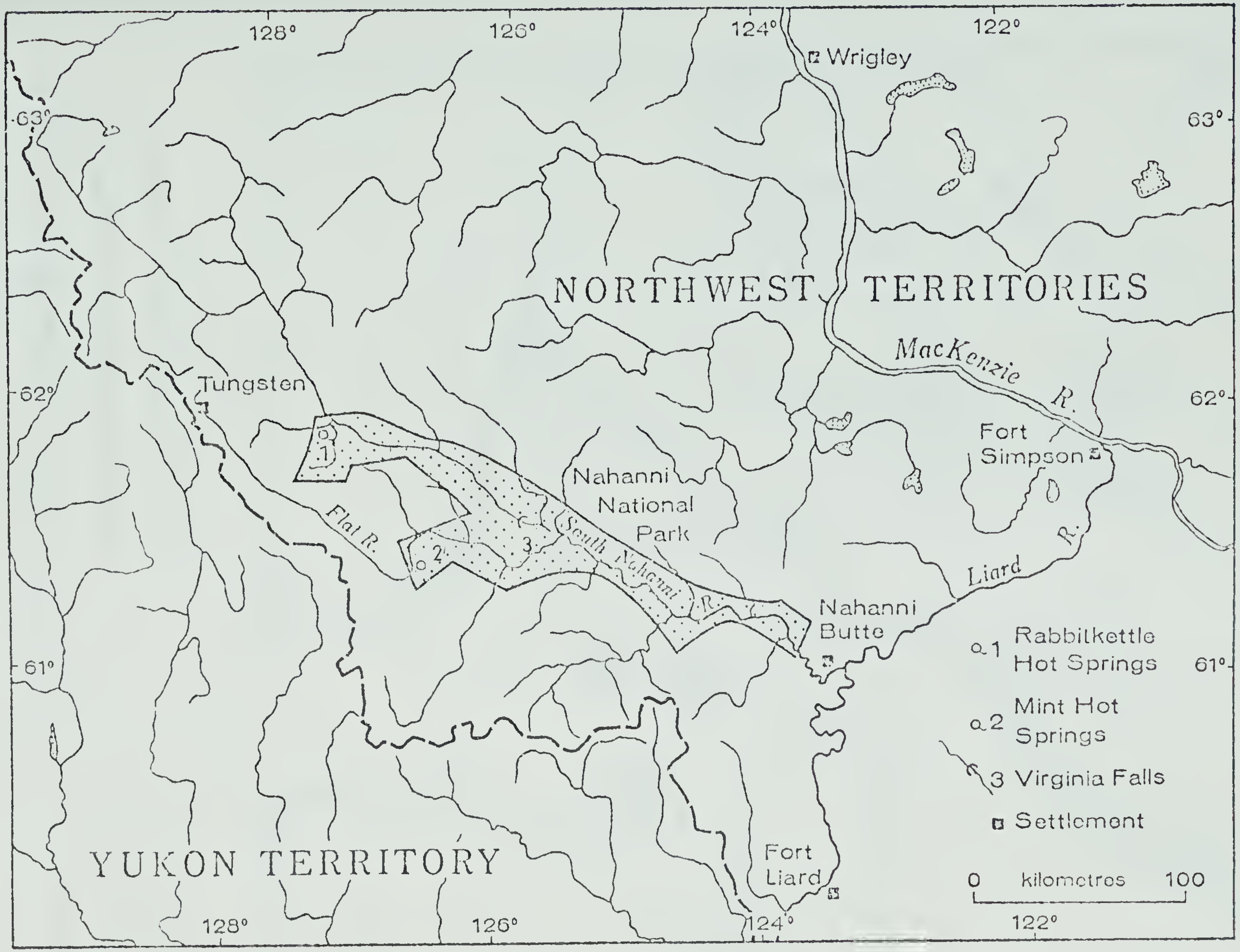


Fig. 0:2 Map of Nahanni River Region

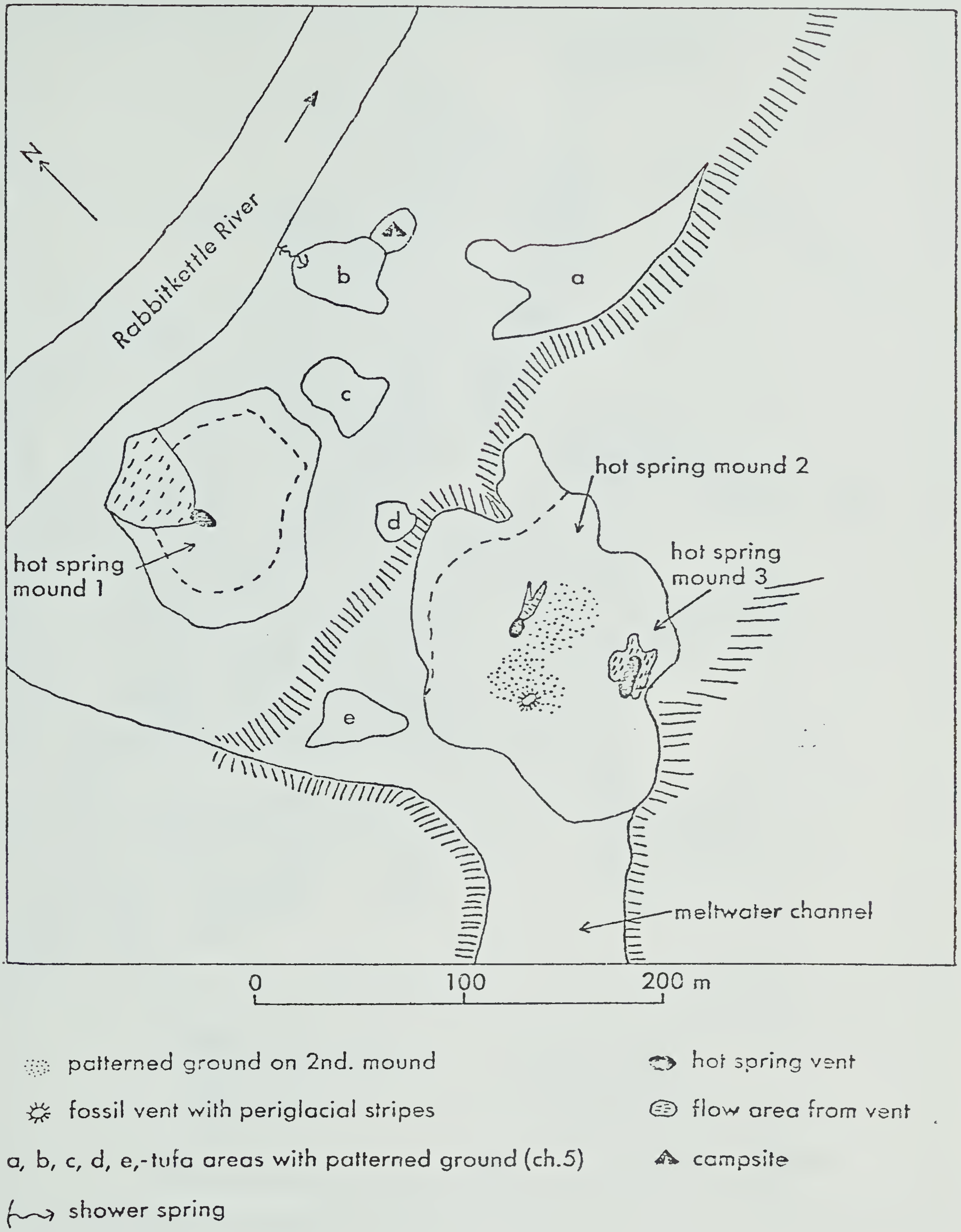


Fig.0:3 Map of Rabbitkettle Hot Spring Region

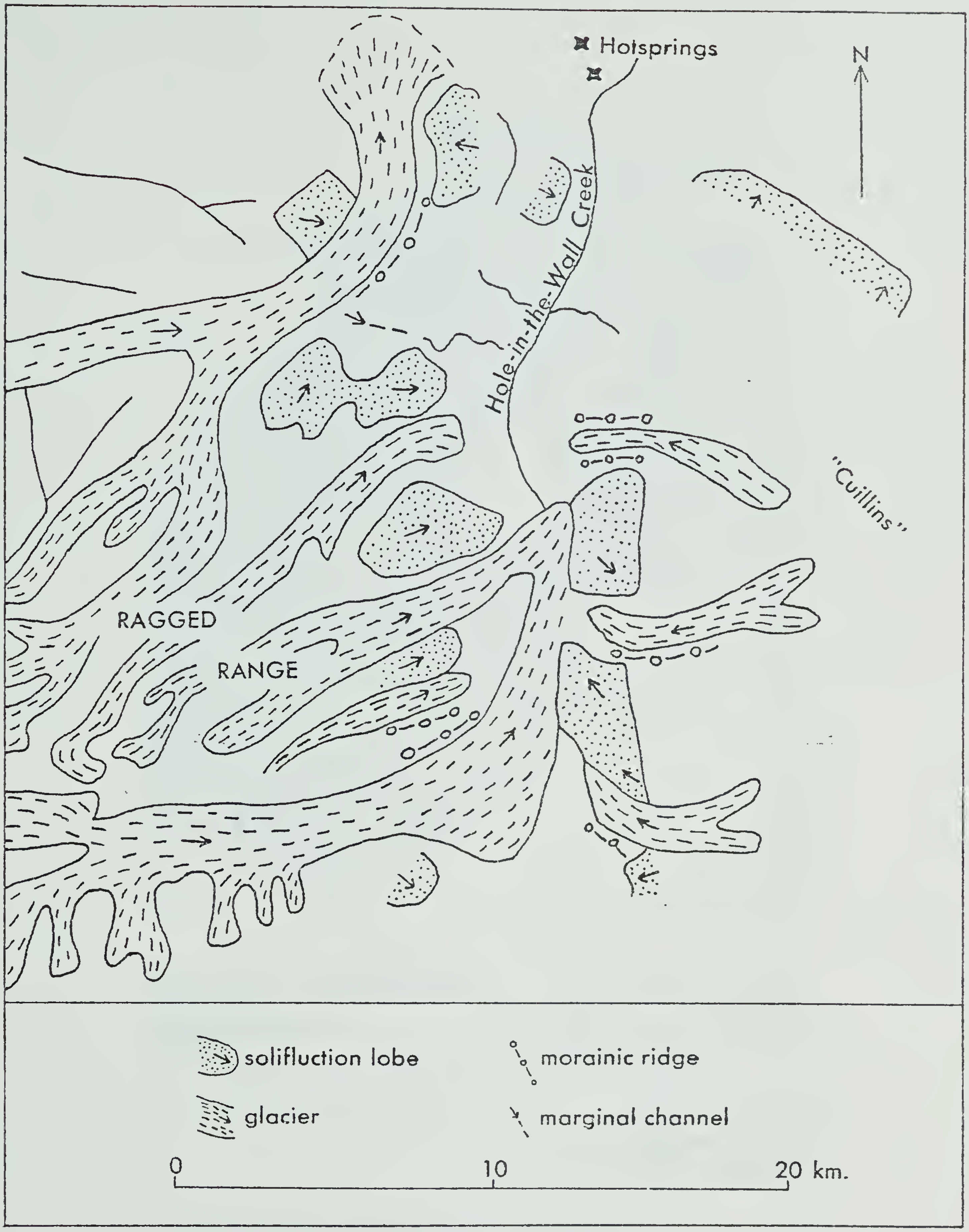


Fig.3:1 Extent of the last Cordilleran glacier penetration into the valley of Hole-in-the-Wall Creek (after Ford, 1976).

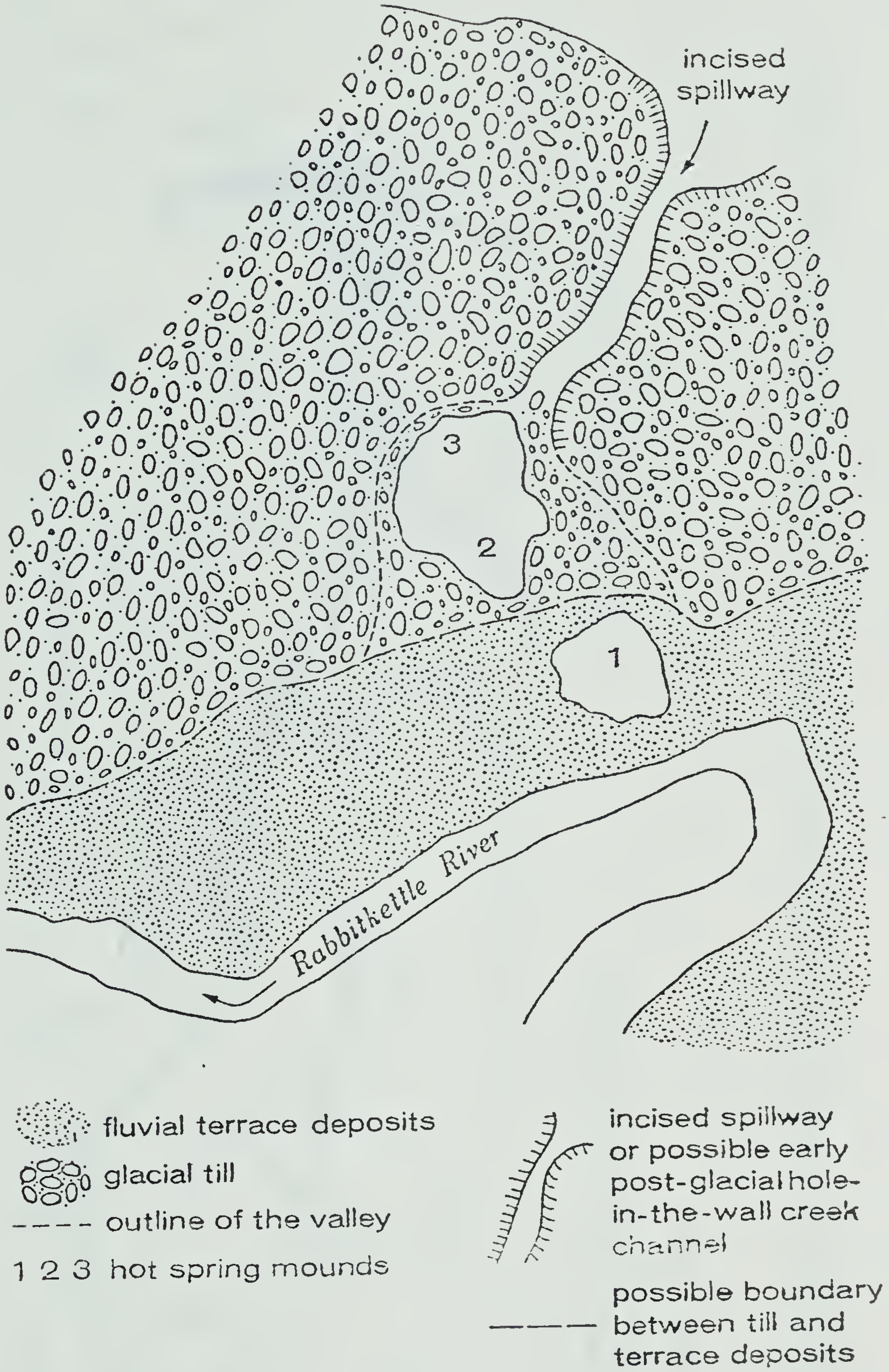
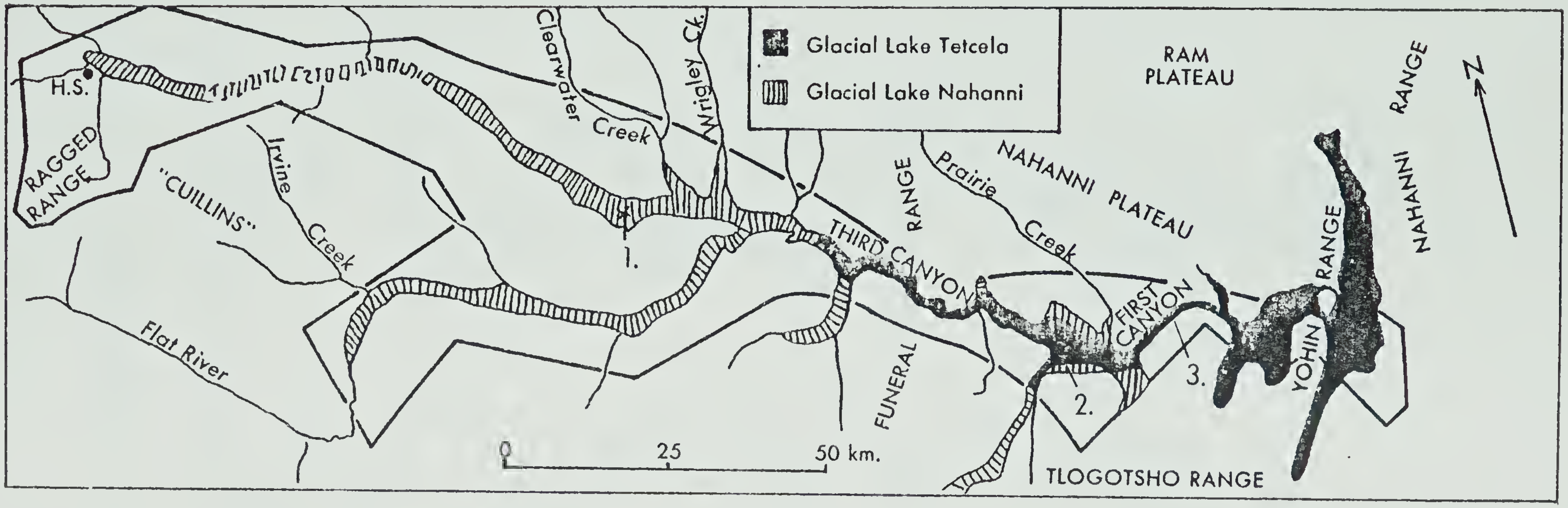

incised spillway
3
2
1
Rabbitkettle River
fluvial terrace deposits
glacial till
---- outline of the valley
1 2 3 hot spring mounds
incised spillway or possible early post-glacial hole-in-the-wall creek channel
possible boundary between till and terrace deposits

Fig. 3:2 Surficial Geology of Hot Spring Area



——Nahanni National Park boundary

•H.S. Rabbitkettle Hot Springs

1. Virgina Falls.

2. Deadman Valley

3. Clausen Creek

Fig.3:3 Extent of Glacial Lake Tetcela (Jackfish Glaciation) and Glacial Lake Nahanni in Nahanni National Park (after Ford, 1976).

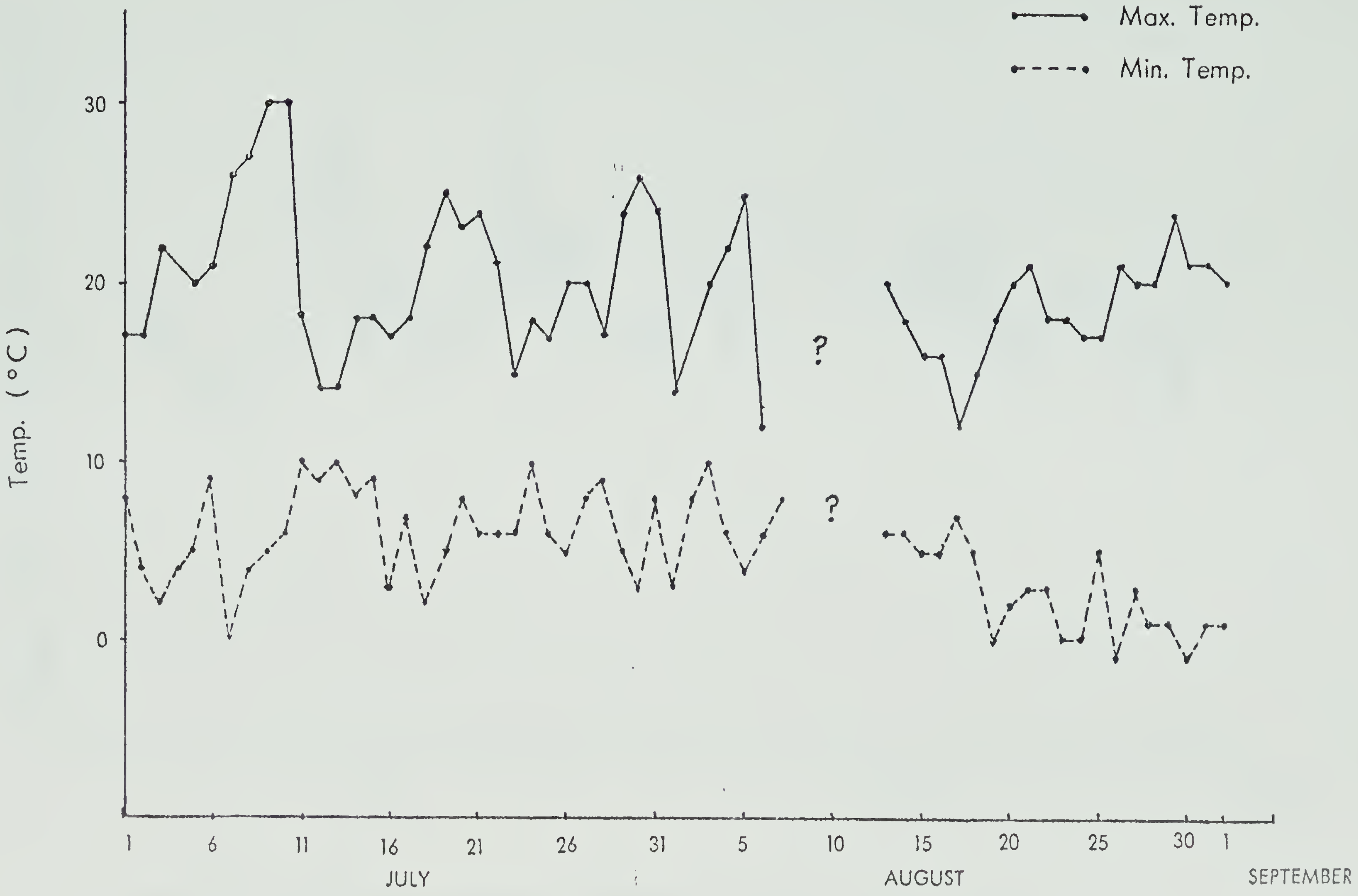


Fig. 3:4 Daily Minimum and Maximum Temperatures for Rabbitkettle Lake, 1 July to 1 September, 1978

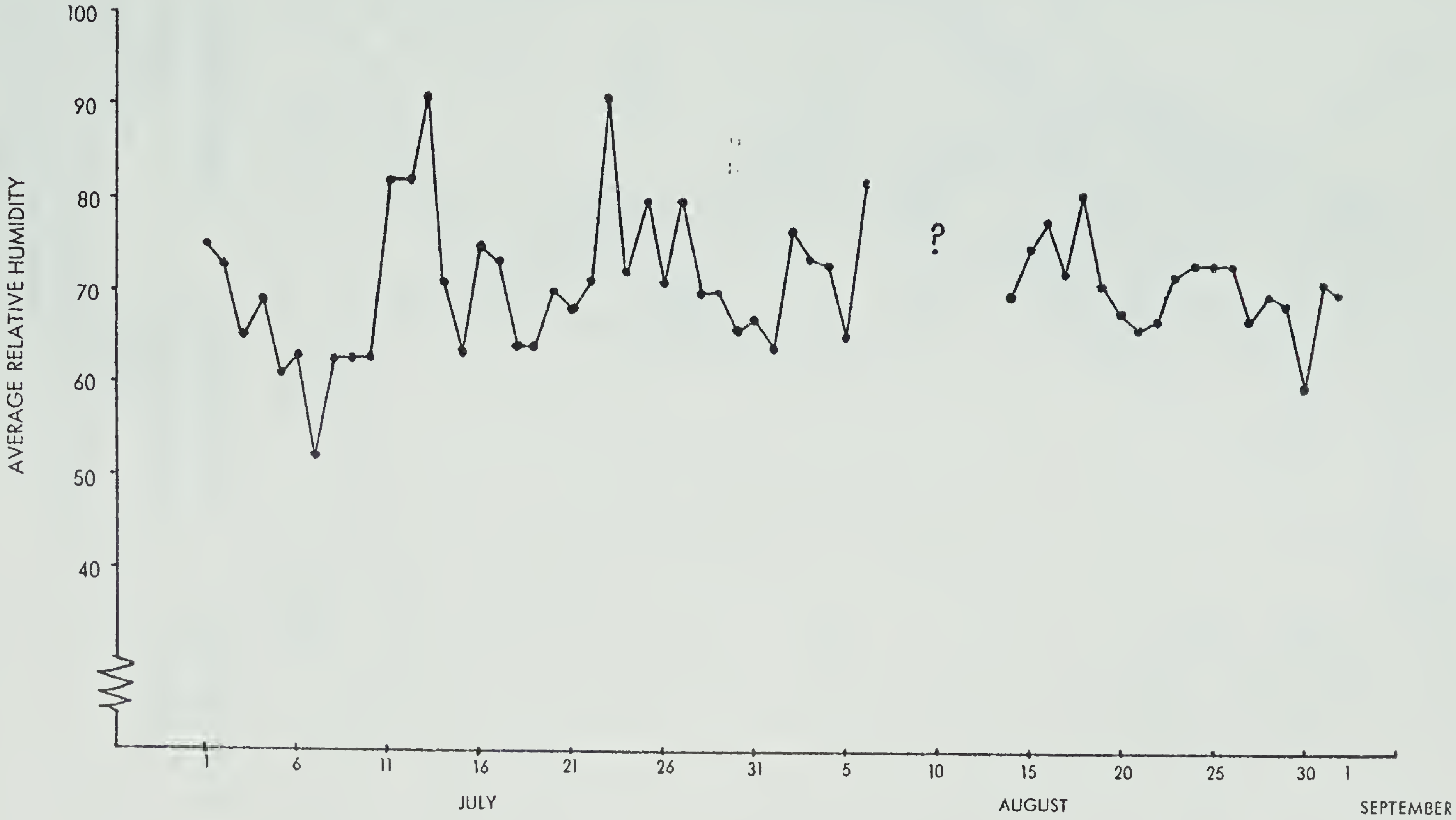
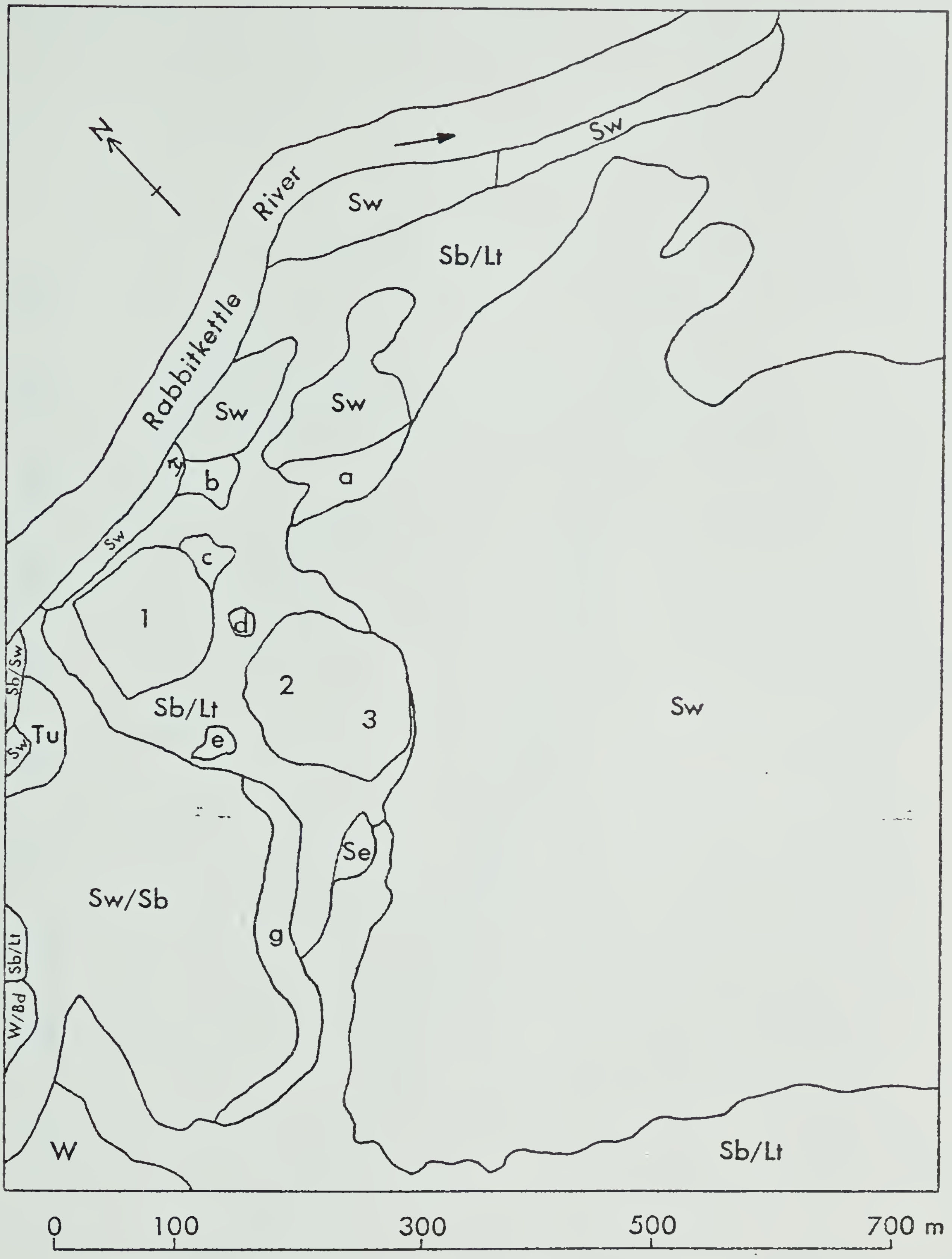


Fig. 3:5. Average Relative Humidity for Rabbitkettle Lake (July and August 1978)



Sw-White Spruce
Lt-Labrador Tea
Bd-Dwarf Birch
Se-Sedge
Sb-Black Spruce
W-Willow
g-grassland
Tu-Tufa
a, b, c, d, e,-tufa areas quoted in Chapter 5
1, 2, 3,-hot spring mounds
↦shower spring

Fig.3:6 Vegetation Map of Hot Spring Area (Marsh and Scotter, 1976)

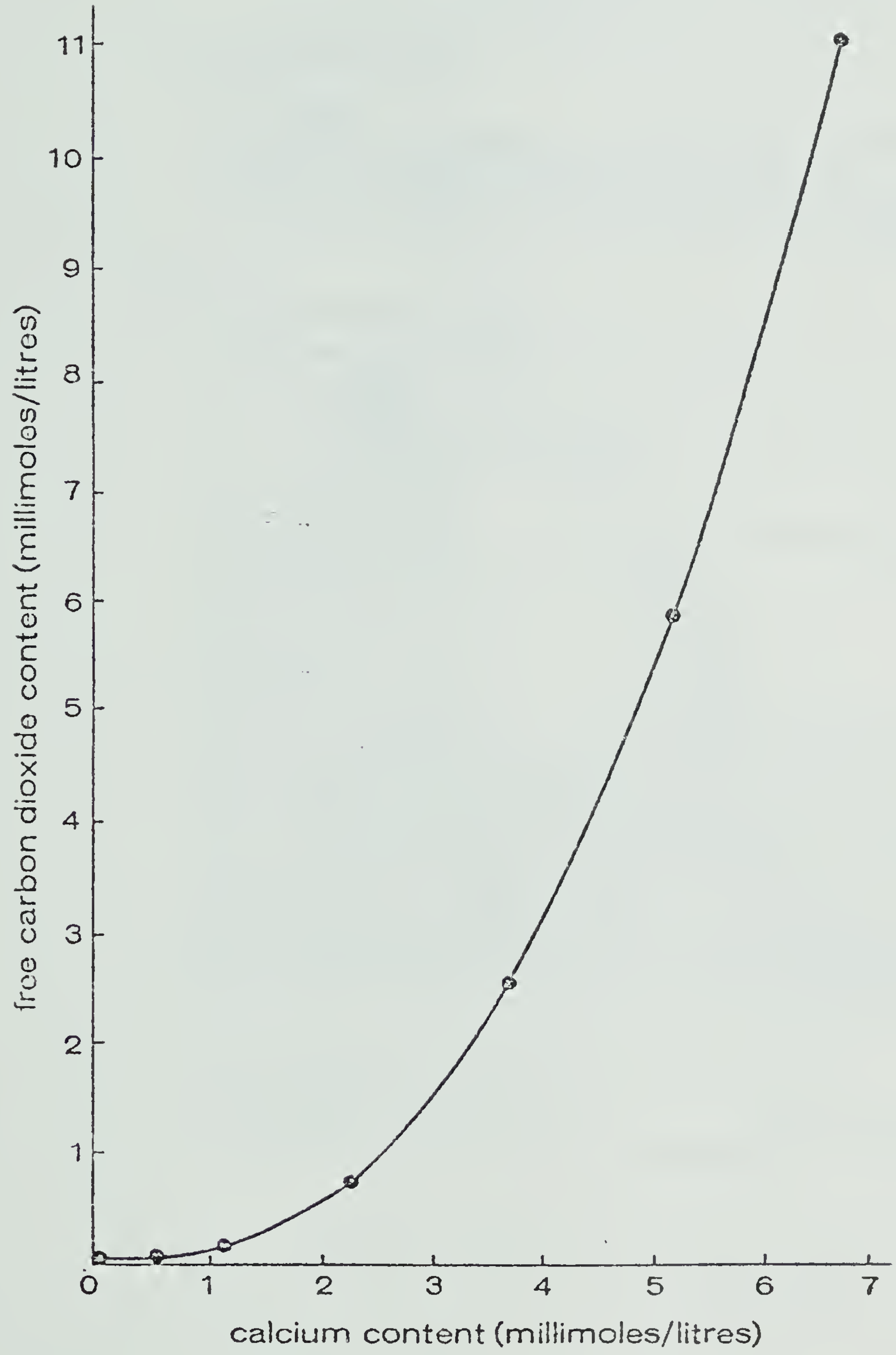
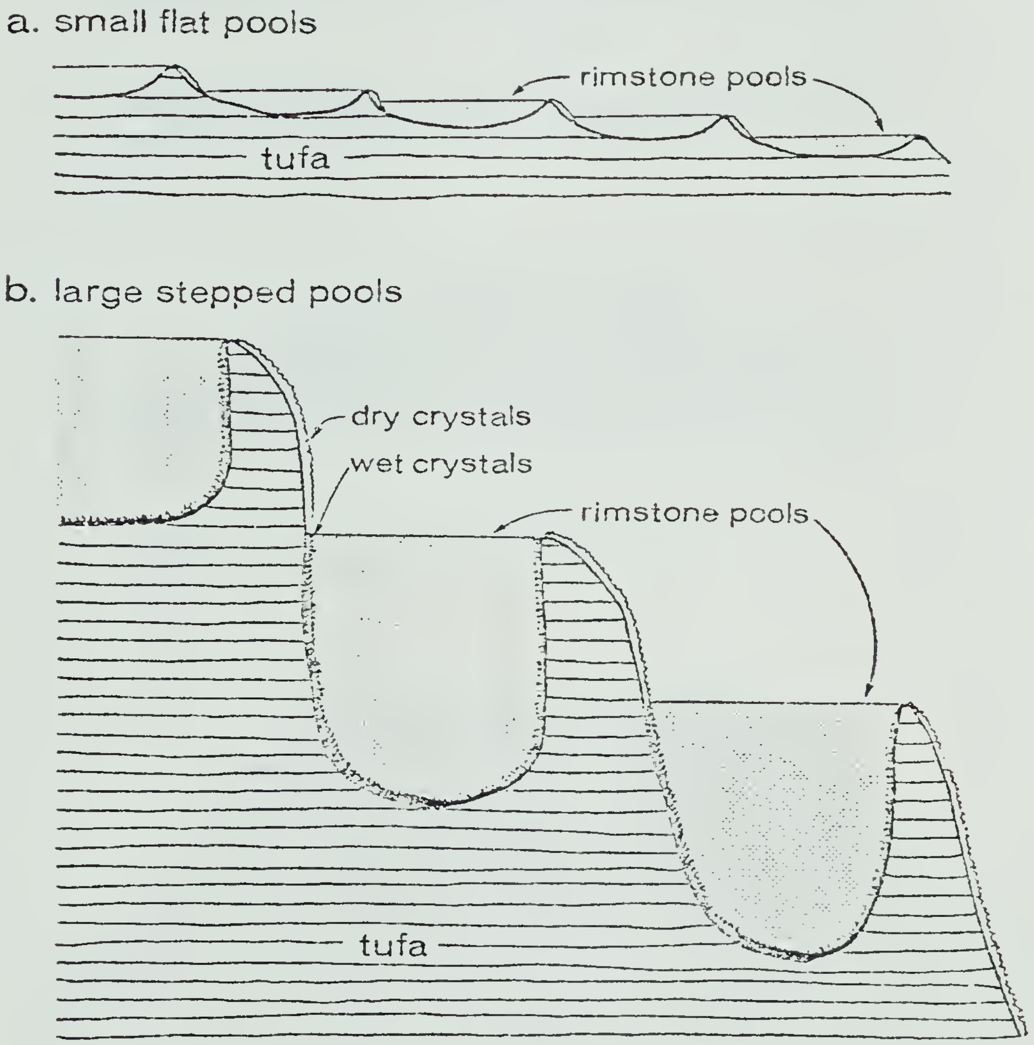


Fig. 4:1 Free CO_2 and calcium (as Ca^{2+} and $CaHCO_3$) in equilibrium in solution of pure calcite at 0° C. (after Picknett, 1964)



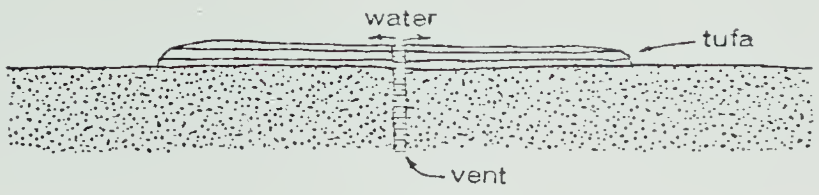
n.b. the wider the pool is, the higher the rim is;
i. e. rim height in b. is higher

(after Warwick, 1952)

(A: small flat pools) (B: large stepped pools)

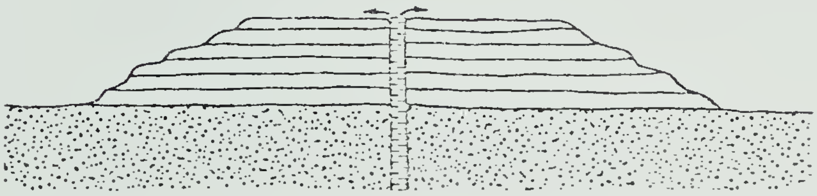
Fig. 4:2 Cross-Section of rimstone pools

1.



mineralized water flows over terrace gravels depositing tufa

2.



tufa mound becomes higher and wider through time

3.

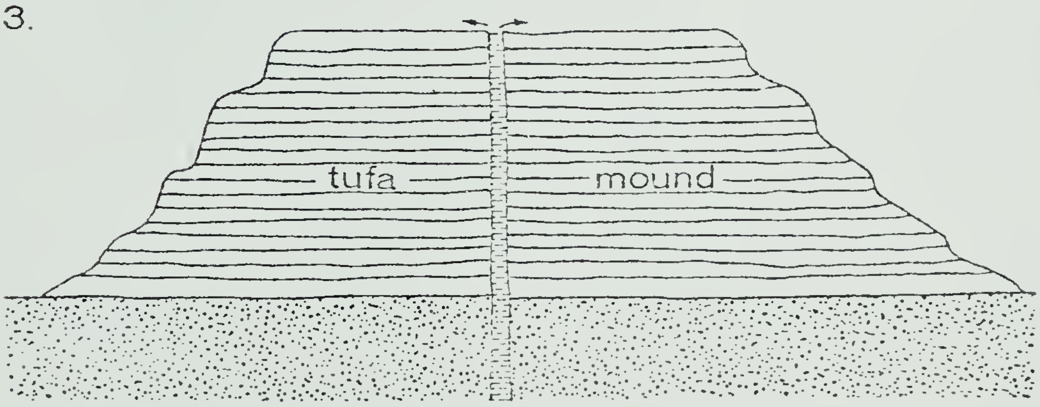


Fig. 4:3 Build-up of tufa on Mound 1

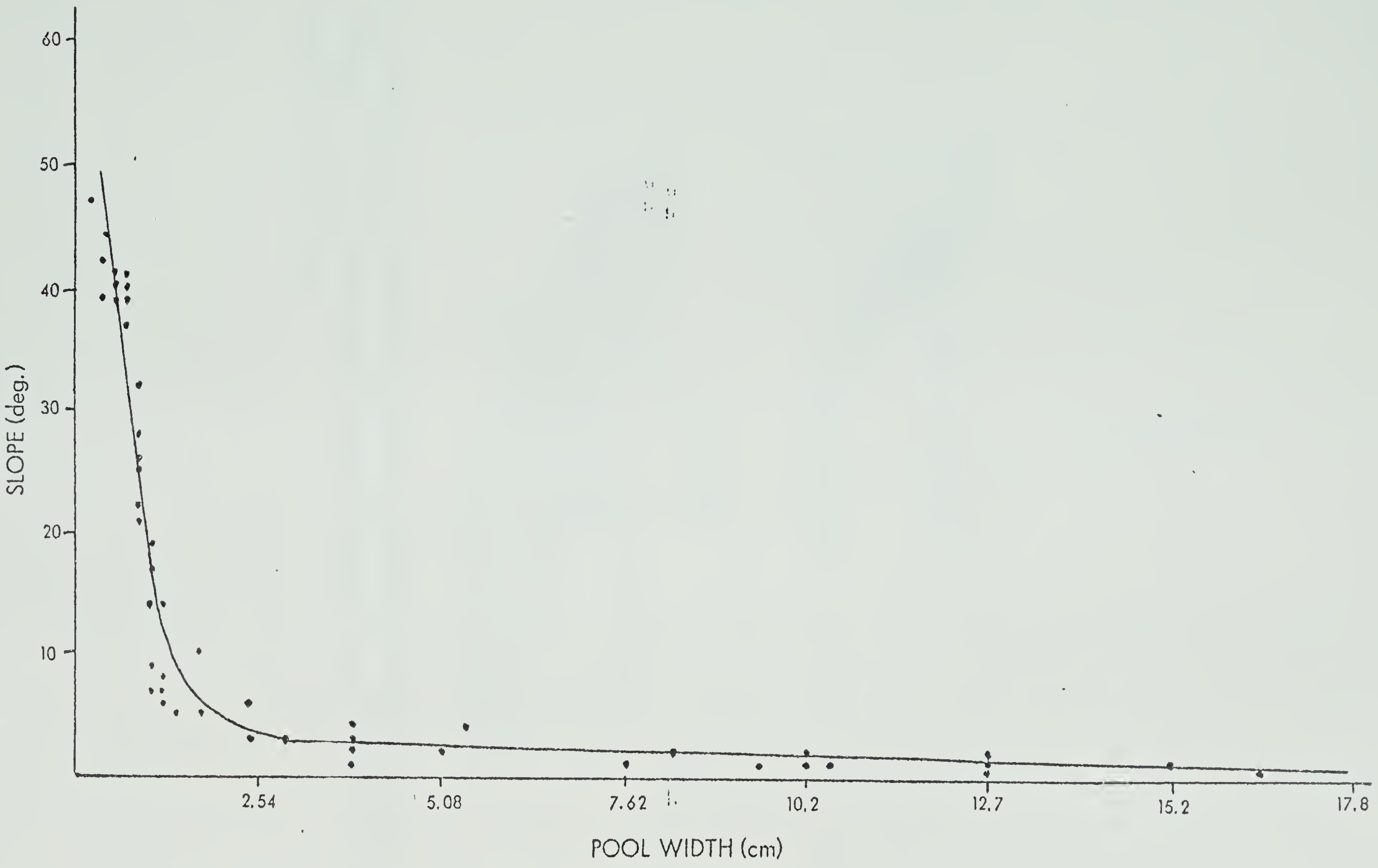


Fig. 4:4 Relationship between pool width and slope of mound

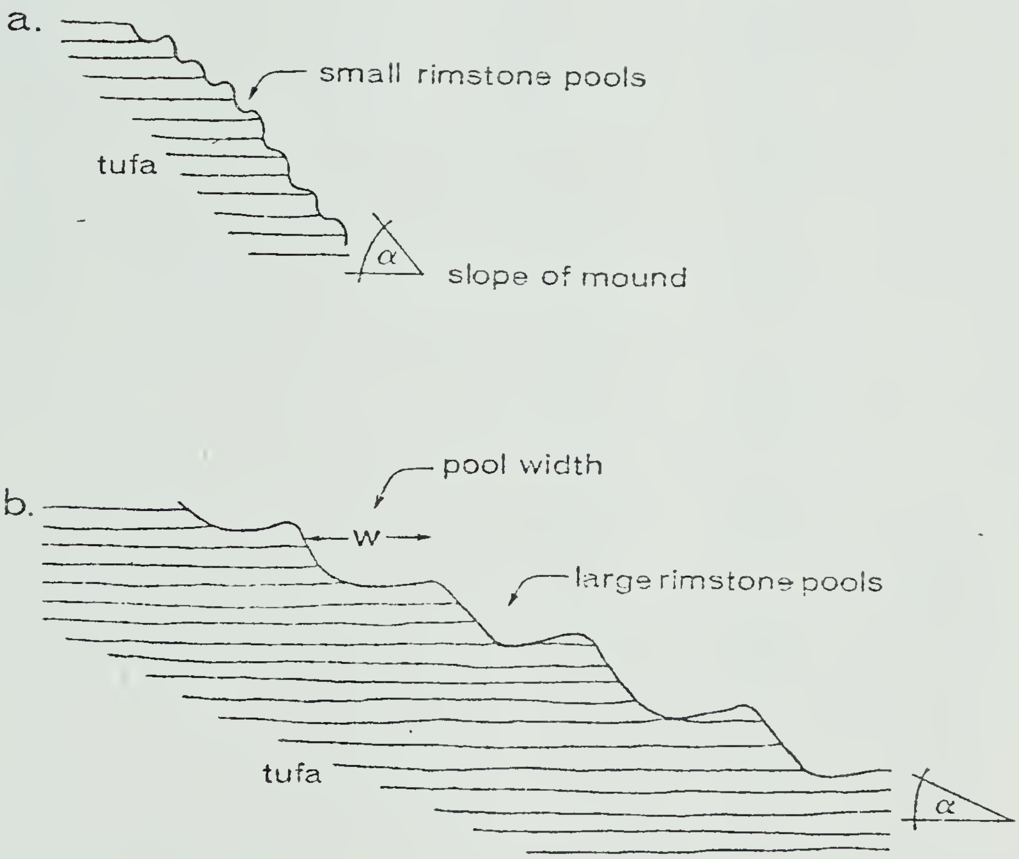


Fig. 4:5 Diagrammatic explanation of the relationship between pool width (w) and slope (α) on Mound 1 In a, pool width is small, hence slope of mound is large. In b, pool width is large, therefore slope is not so great.

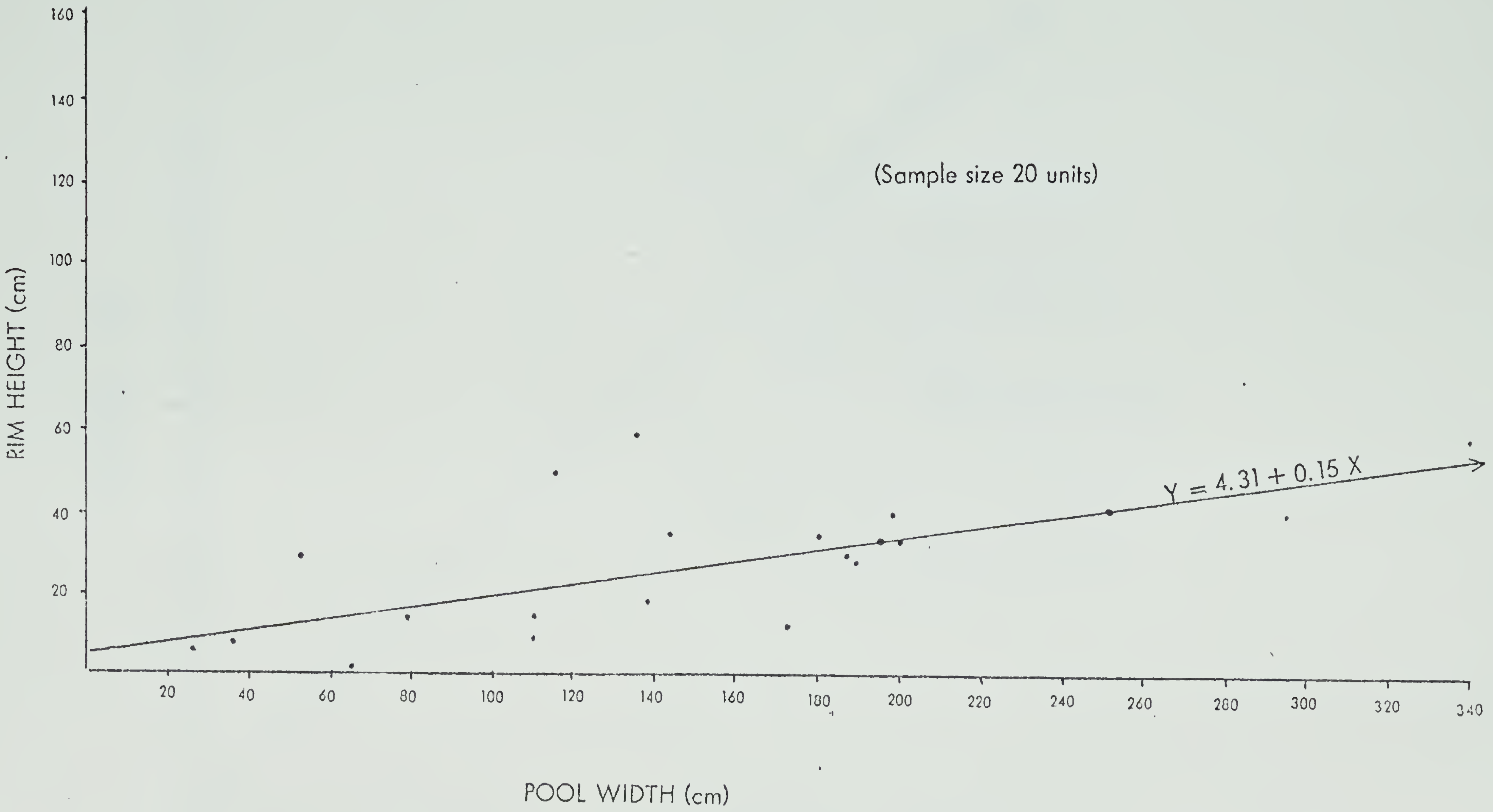
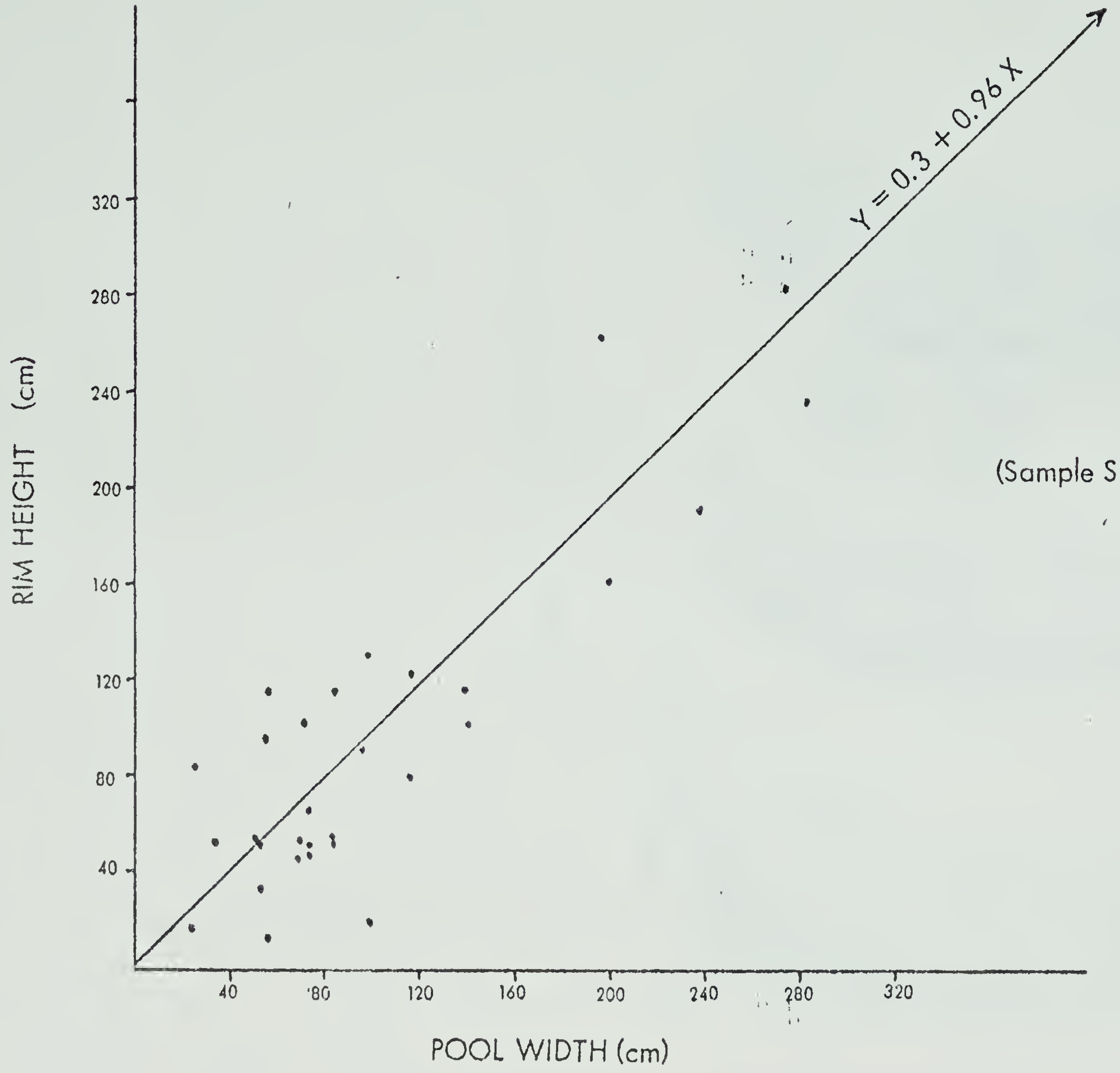


Fig 4:6 Relationship between Pool Width and Rim Height for Mound 1, (upper portion).



(Sample Size 30 units).

Fig. 4:7. Relationship between Pool Width and Rim Height for Mound 1, (lower portion).

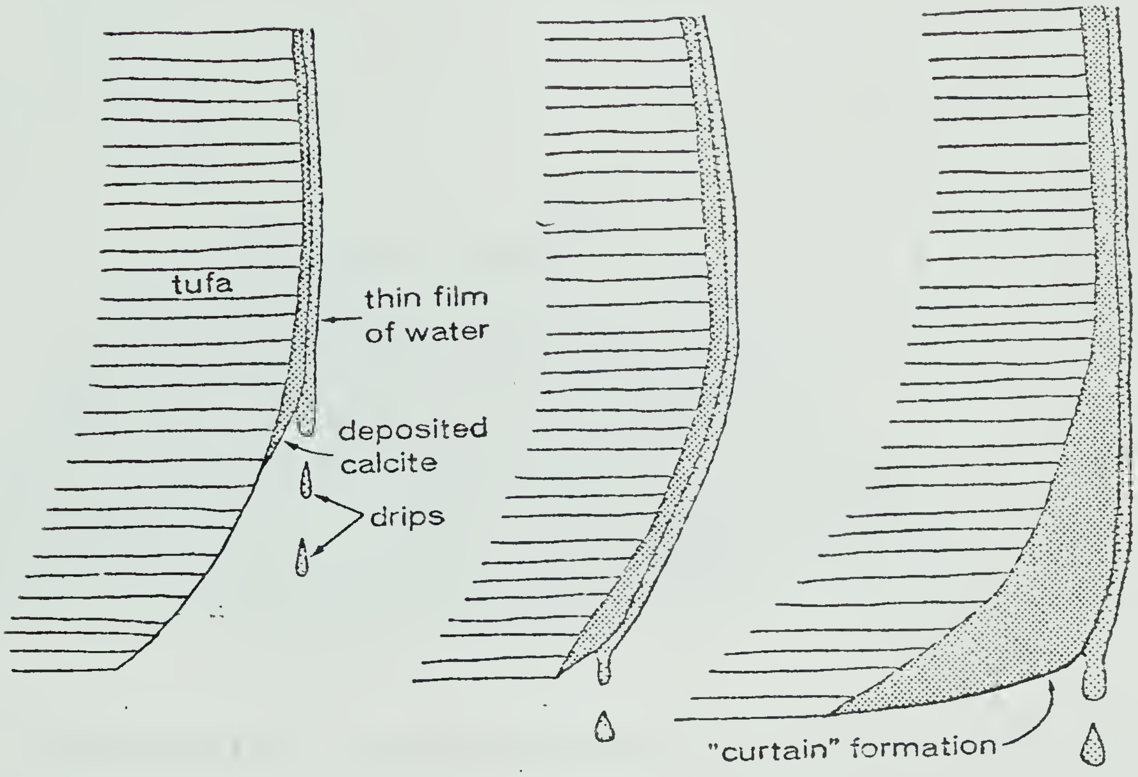


Fig. 4:8 Formation of curtains in tufa.

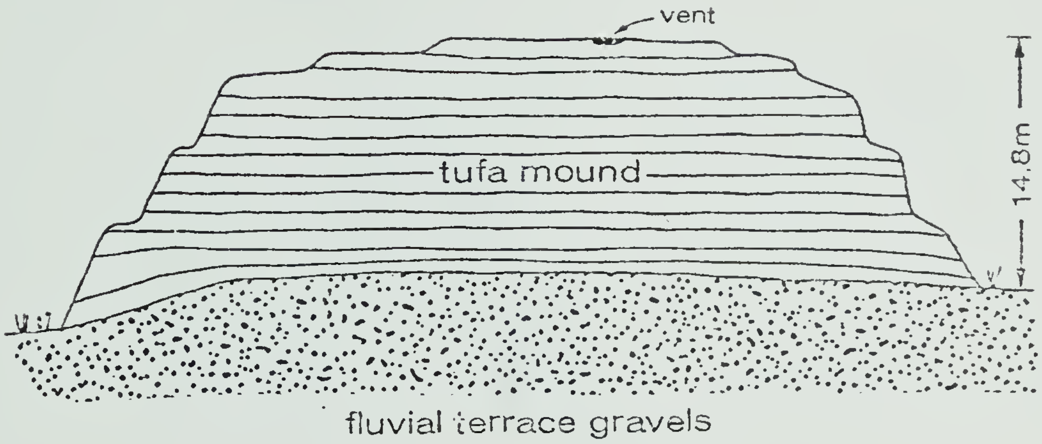


Fig 4:9 Relationship between asymmetry of Mound 1 and underlying fluvial terrace

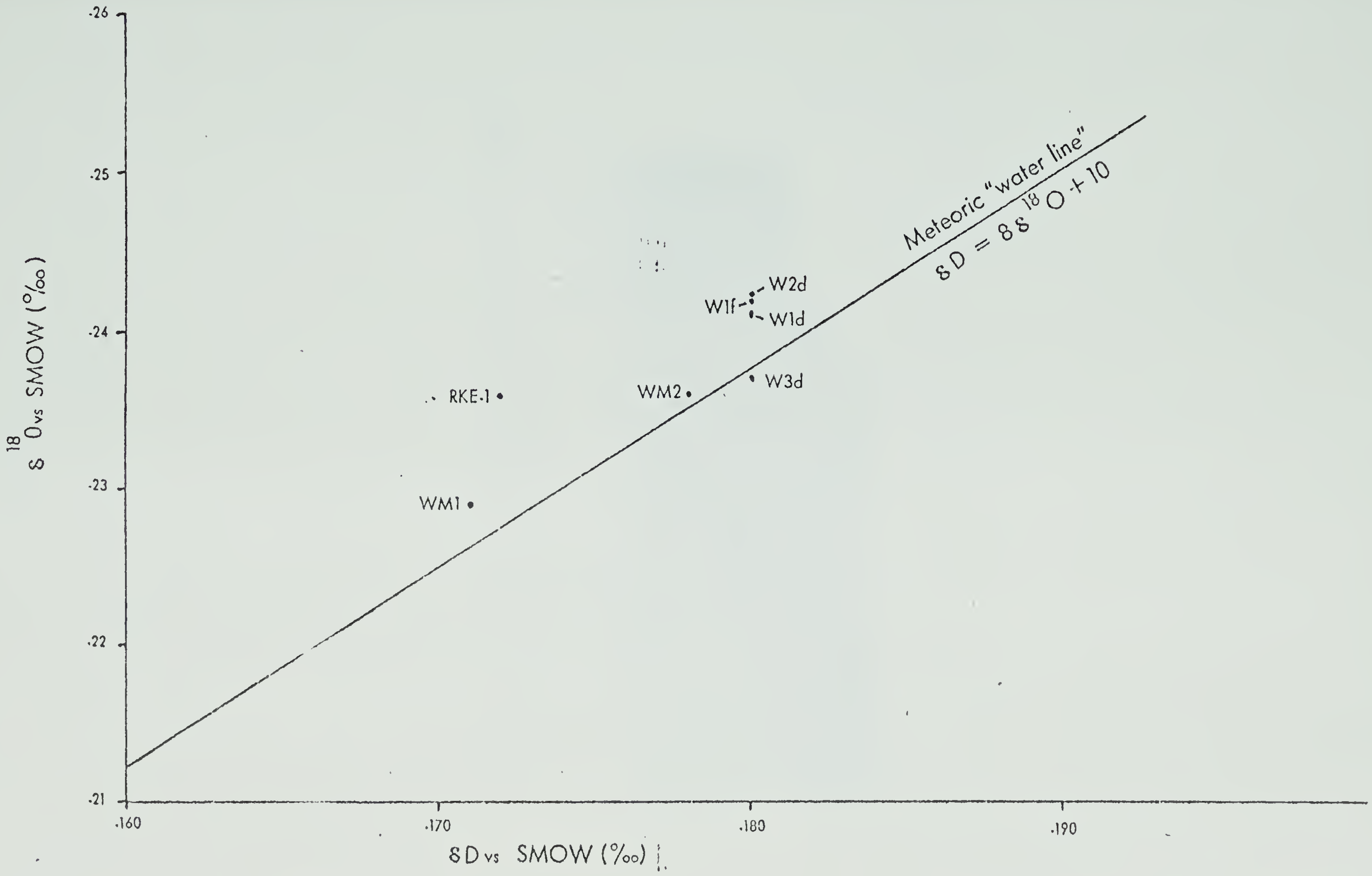


Fig. 4:10 Hydrogen Isotopic Composition vs. Oxygen Isotopic Composition of Waters from Wild Mint and Rabbitkettle Hot Springs.

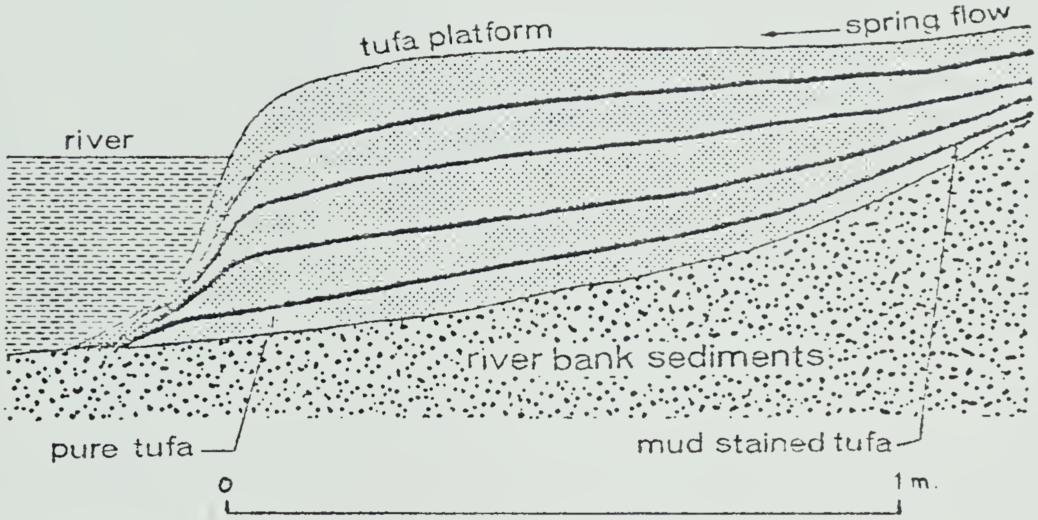


Fig. 4:11 Cross-section of tufa platform formed by Shower Spring.

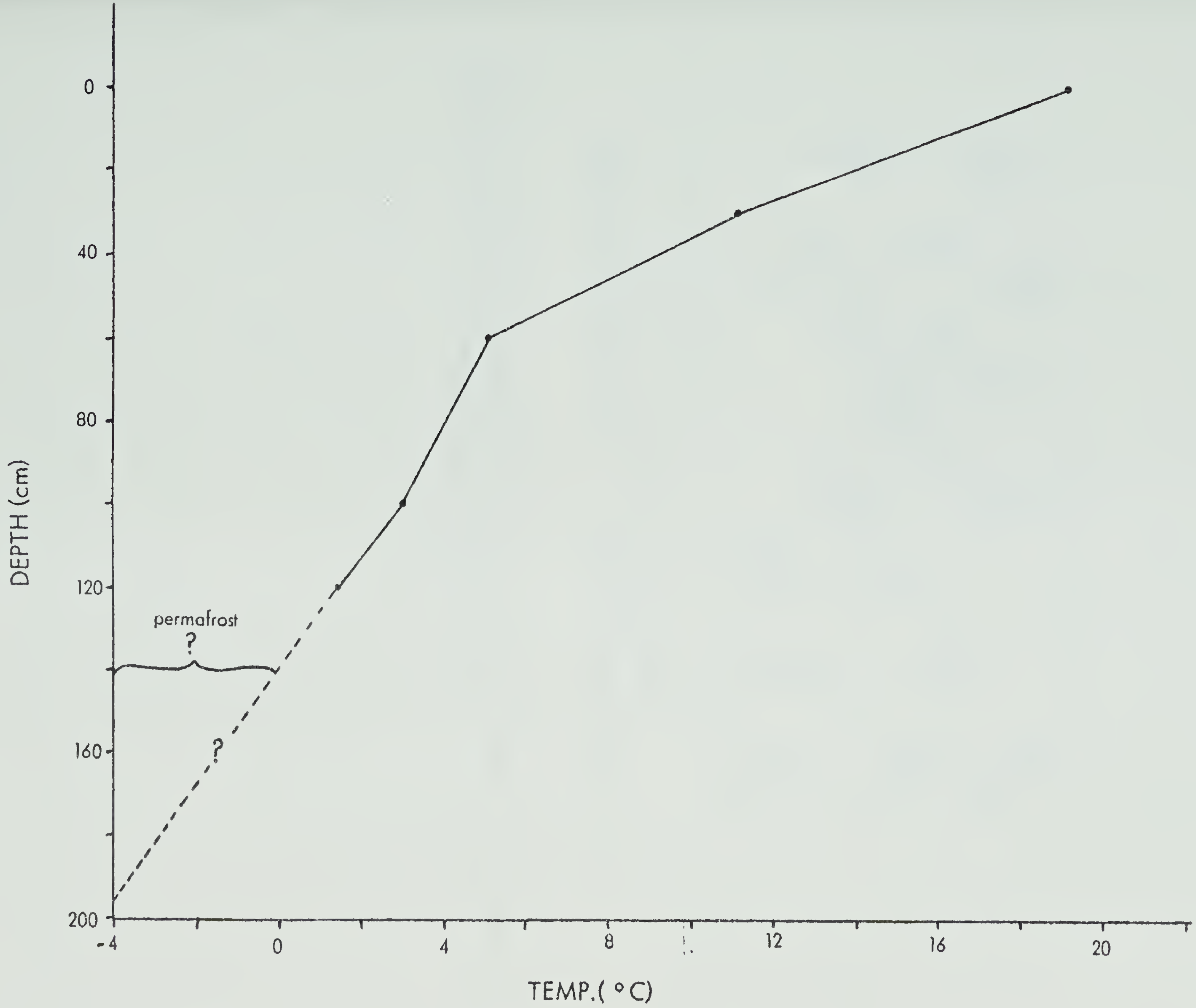


Fig. 5:1 Graph of soil temperatures vs. soil depth (19th July 1978.)

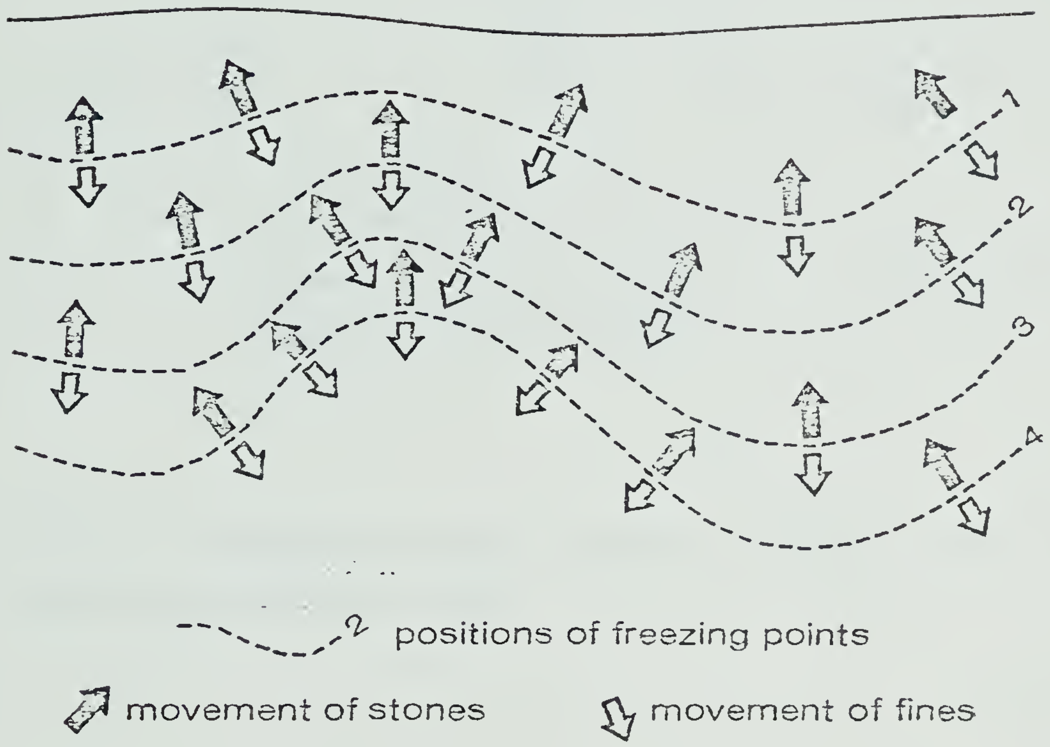


Fig. 5: 2. Radial movement model of patterned ground. Formation occurs when there is sorting in conjunction with inclined freezing fronts. (Nicholson 1976)

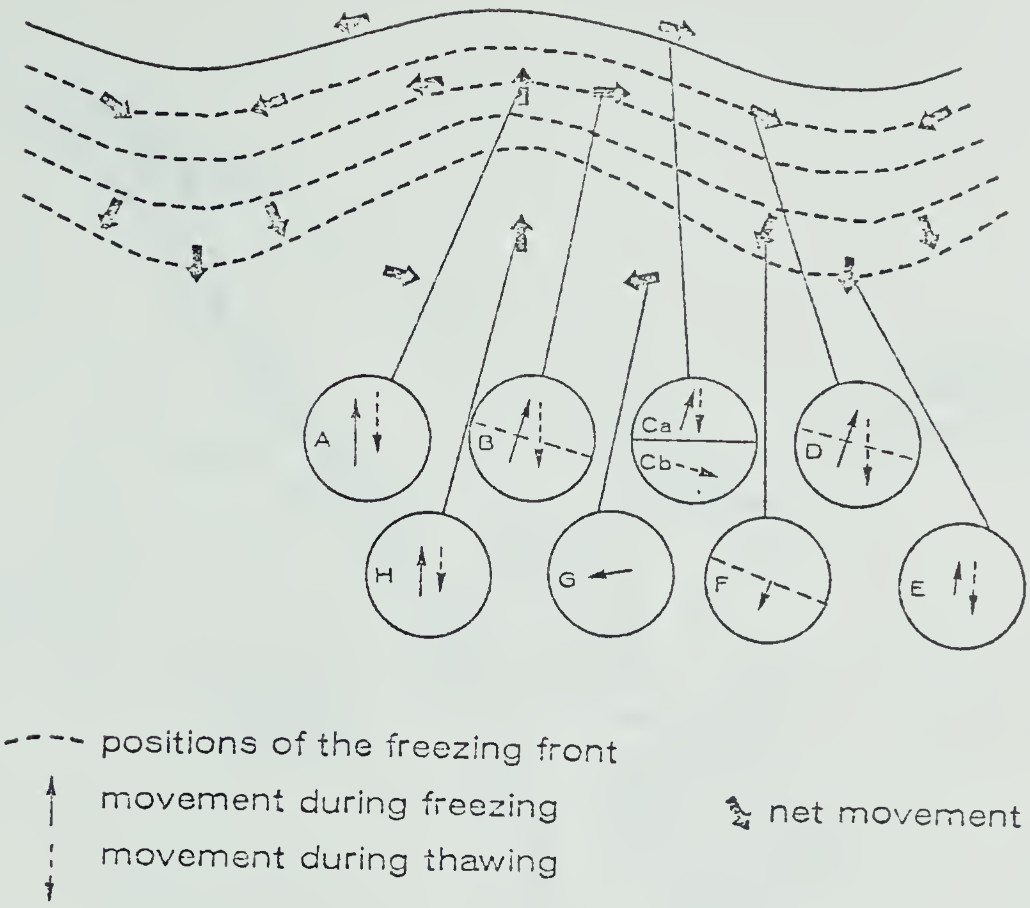


Fig. 5: 3. Summary of movements suggesting a circulatory model of patterned - ground development (Nicholson 1976)

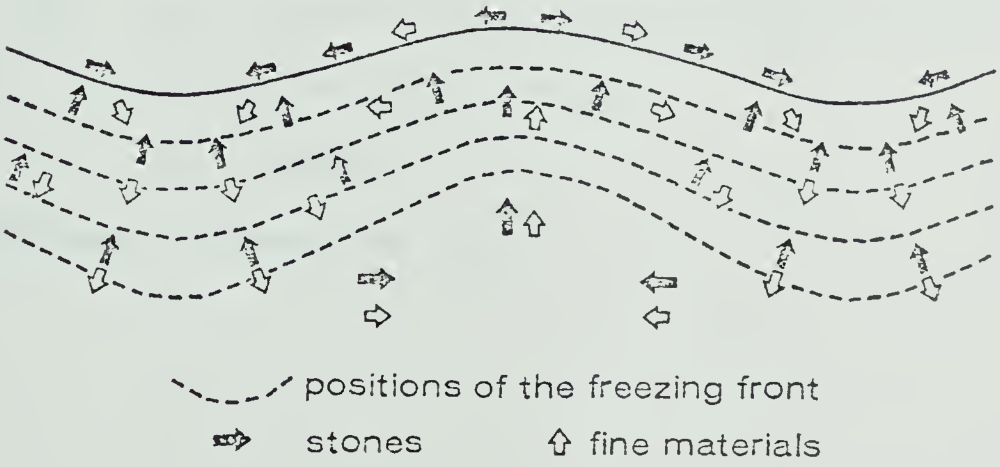


Fig. 5: 4. Combination of patterned ground development showing the dominantly radial movement of stones (cf. Fig. 5:3) and the circulatory movement of finer materials (cf. Fig. 5: 4) (Nicholson 1976)

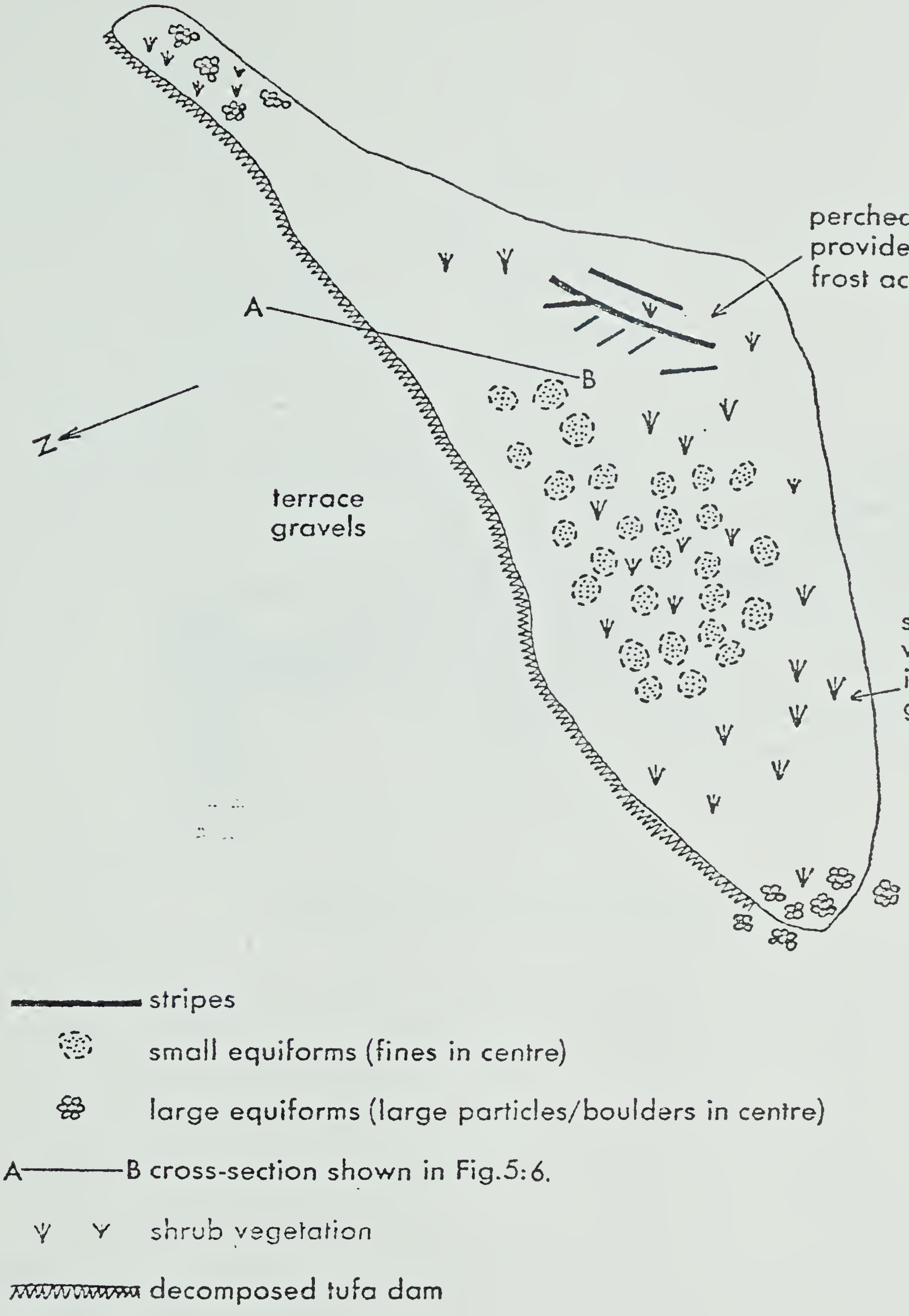

perched watertable provides moisture for frost action
A
B
N
terrace gravels
sparse shrub vegetation in intra-patterned ground area
stripes
small equiforms (fines in centre)
large equiforms (large particles/boulders in centre)
A——B cross-section shown in Fig.5:6.
shrub vegetation
decomposed tufa dam

Fig.5:5. Sketch of tufa area 'a'

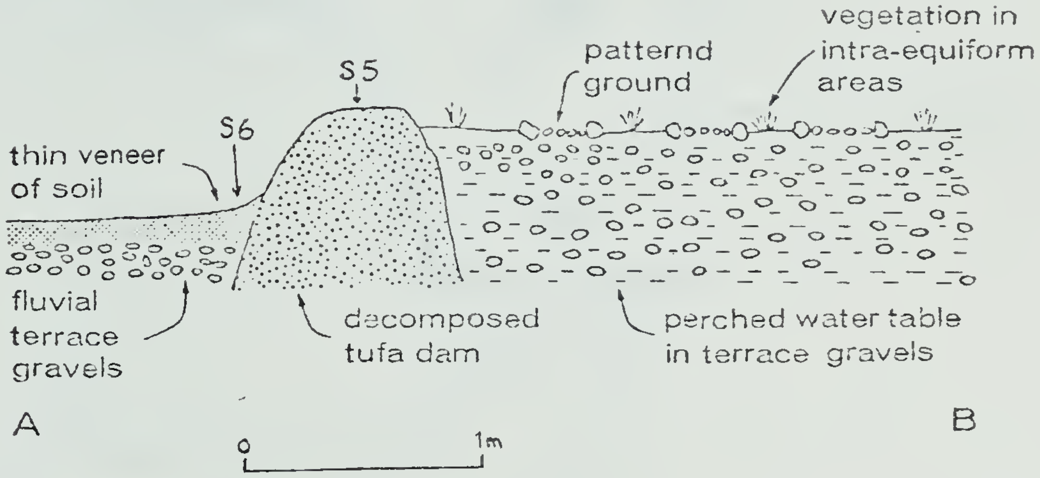


Fig. 5:6 Cross-section of tufa area "a".

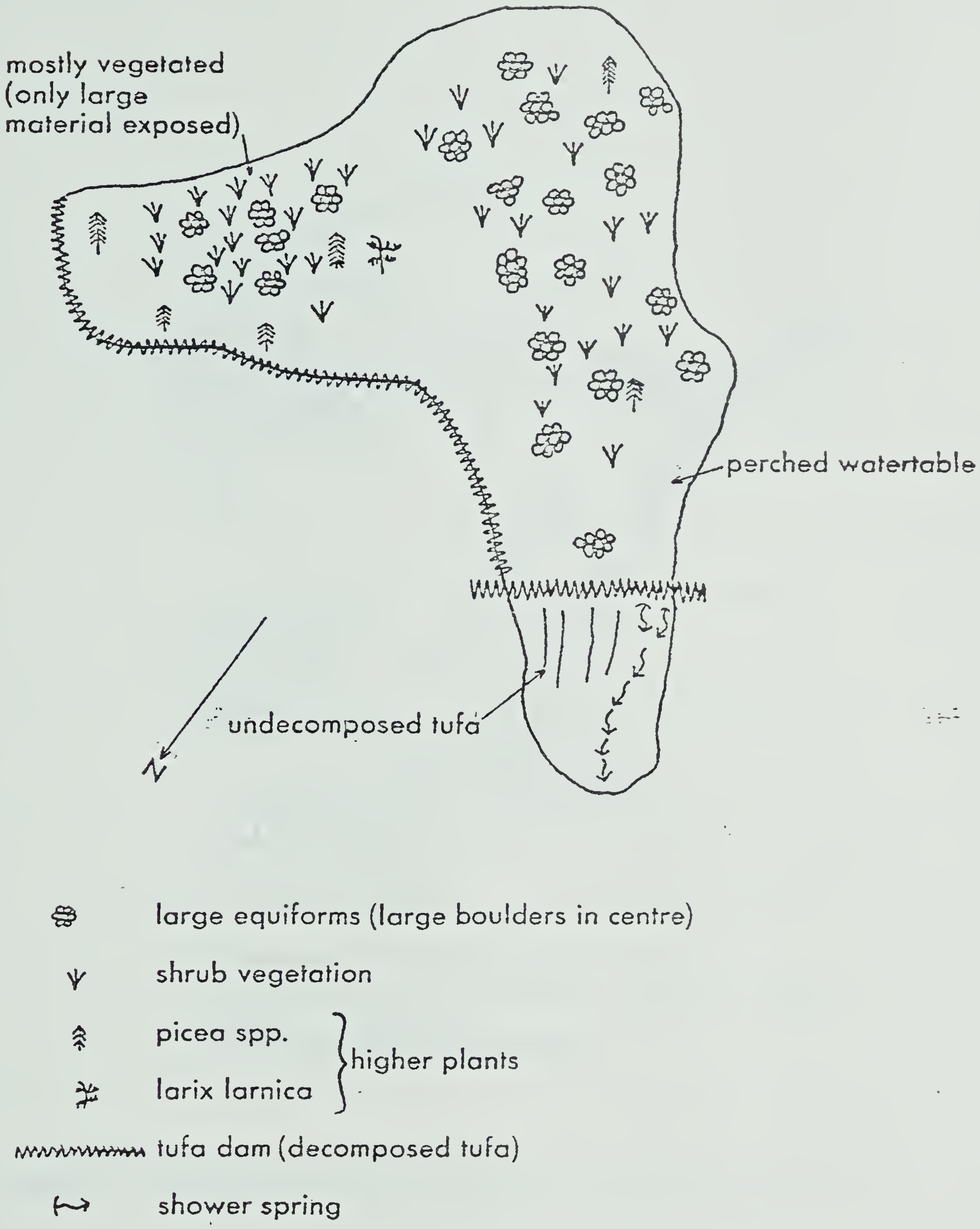

mostly vegetated (only large material exposed)
perched watertable
undecomposed tufa
N
large equiforms (large boulders in centre)
shrub vegetation
picea spp.
larix larnica
higher plants
tufa dam (decomposed tufa)
shower spring

Fig.5:7 Sketch of tufa area 'b'

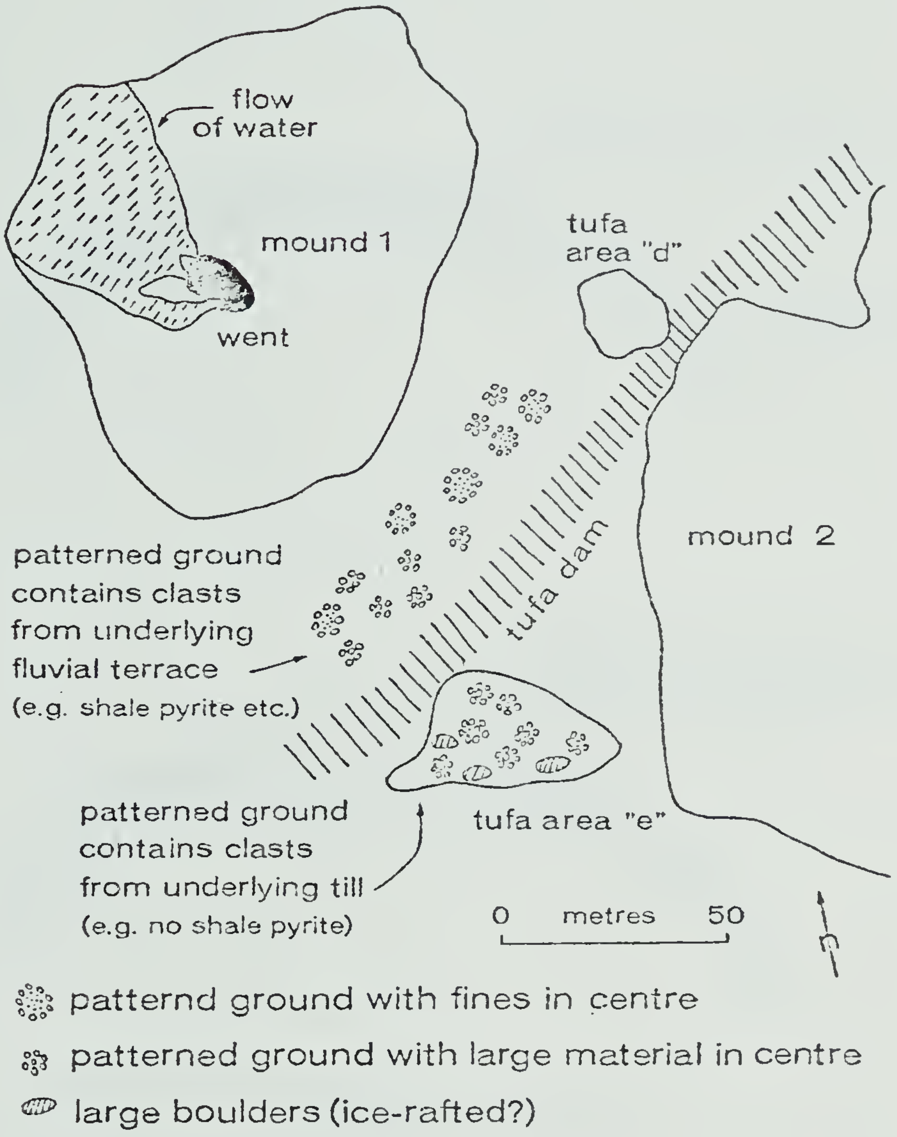

flow of water
mound 1
went
tufa area "d"
mound 2
tufa dam
patterned ground contains clasts from underlying fluvial terrace (e.g. shale pyrite etc.)
patterned ground contains clasts from underlying till (e.g. no shale pyrite)
tufa area "e"
0 metres 50
patternd ground with fines in centre
patterned ground with large material in centre
large boulders (ice-rafted?)

Fig.5:8 Patterned ground above and below tufa dam near tufa area "e"

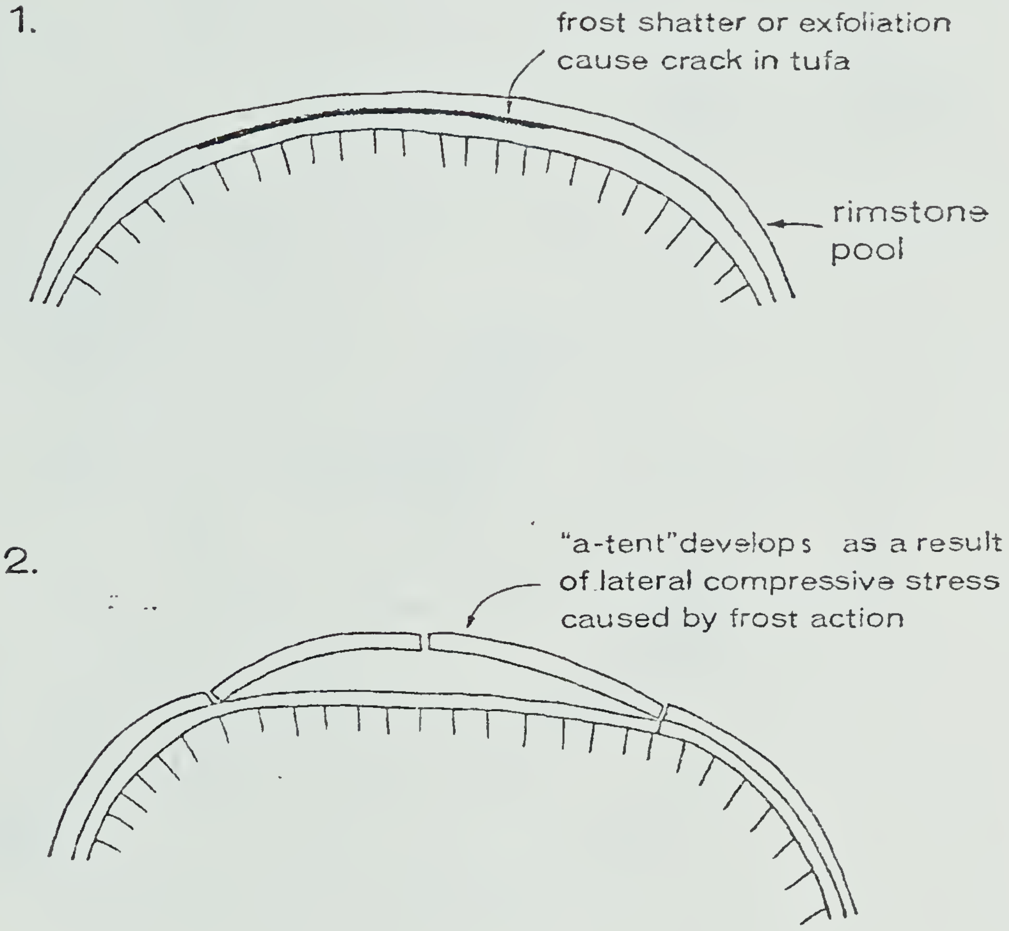

1.
frost shatter or exfoliation cause crack in tufa
rimstone pool
2.
"a-tent" develops as a result of lateral compressive stress caused by frost action

Fig. 5: 9 Development of "A-tents".

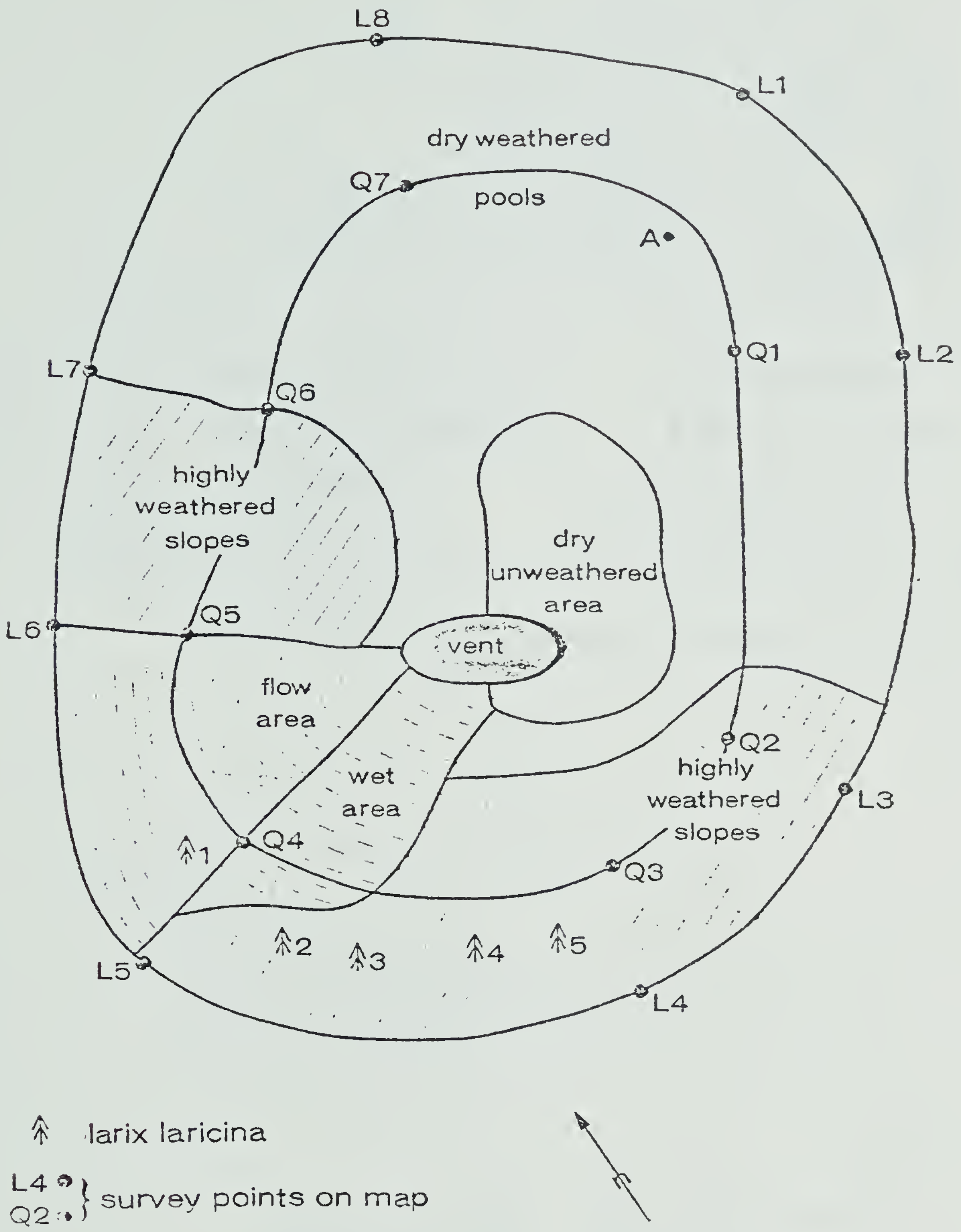


Fig. 6:1 Map of different vegetation habitats on Mound 1.

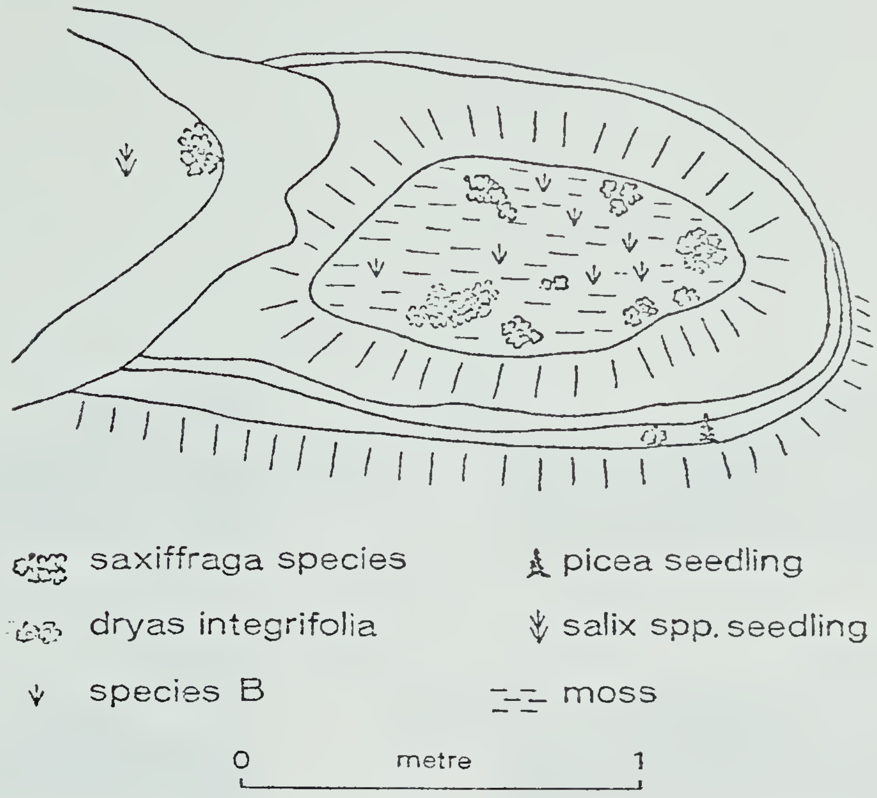


Fig. 6:2 Vegetation colonization in fossil pool on Mound 1

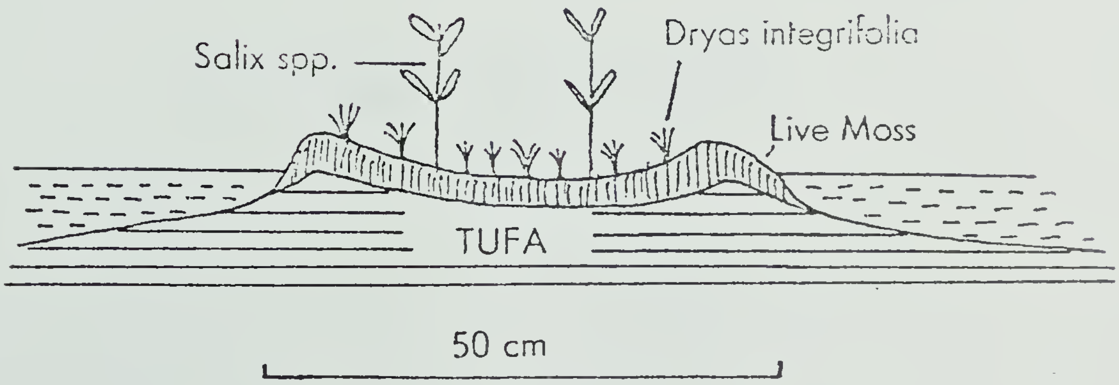


Fig. 6:3 Vegetation mound or hillock

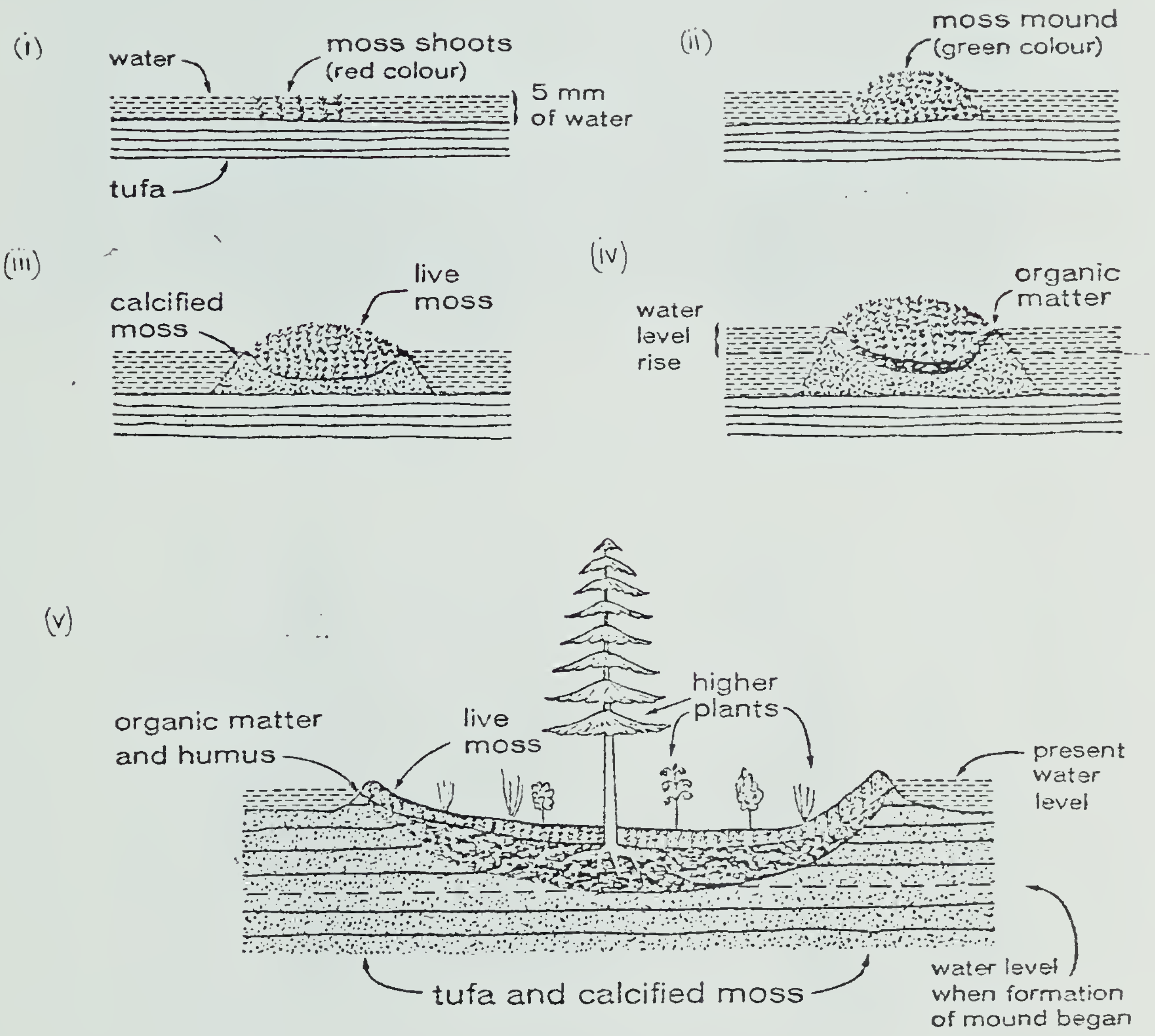
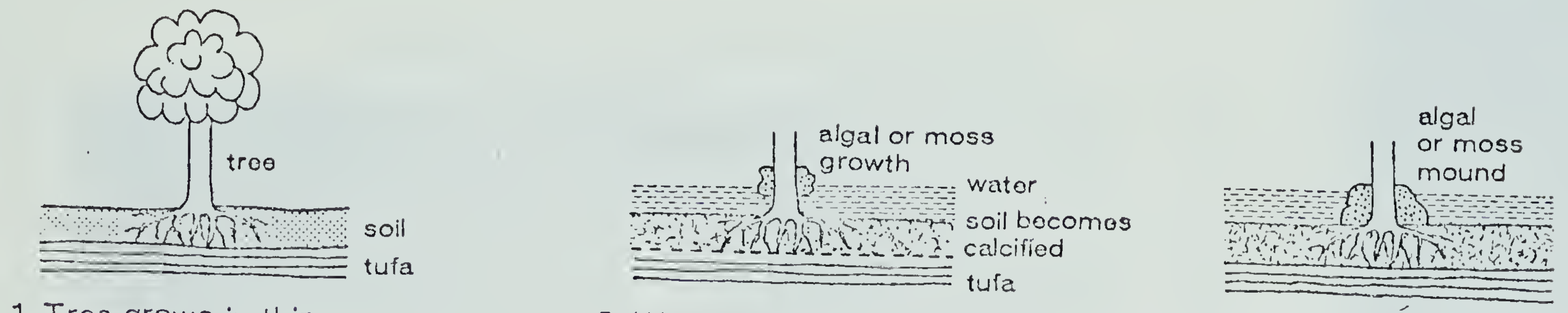


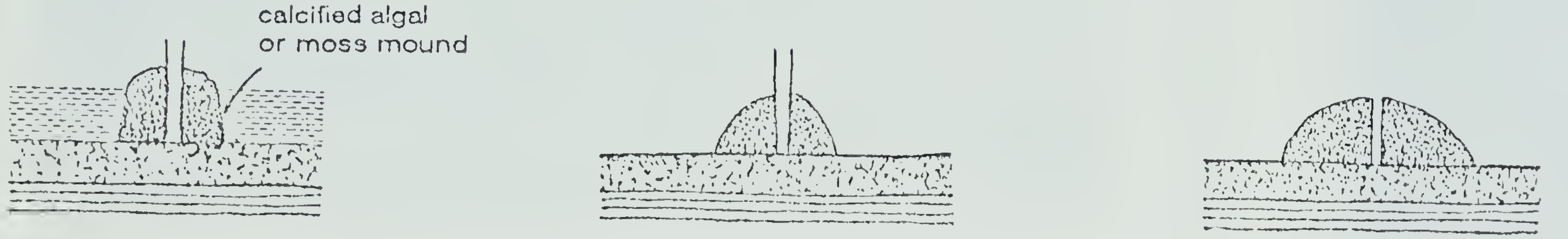
Fig. 6:4 Origin of vegetation mounds.



1. Tree grows in thin veneer of soil on tufa.

2. Water invades area, drowning the tree and depositing $CaCo_3$ which calcifies the soil. Algae and moss grow on dead tree.

3. Algal or moss mound grows in water on dead tree.



4. Algal or moss mound Increases in size as water level rises. Part of mound beneath water surface becomes calcified.

5. Water regresses and moss or algae dies, leaving calcified vegetation mound.

6. Tree eventually rots, leaving a hole in centre of vegetation mound.

Fig. 6:5 Origin of "nippleoid" vegetation mounds.

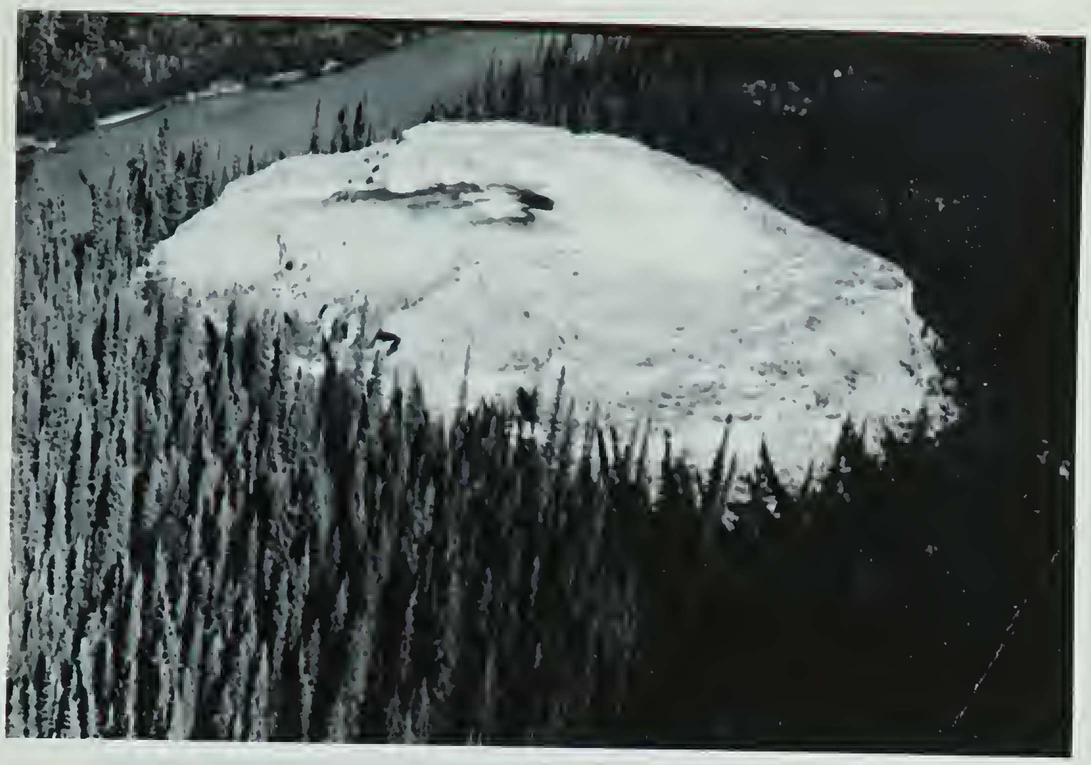


Plate 1. Rabbitkettle Hot Spring Mound 1.

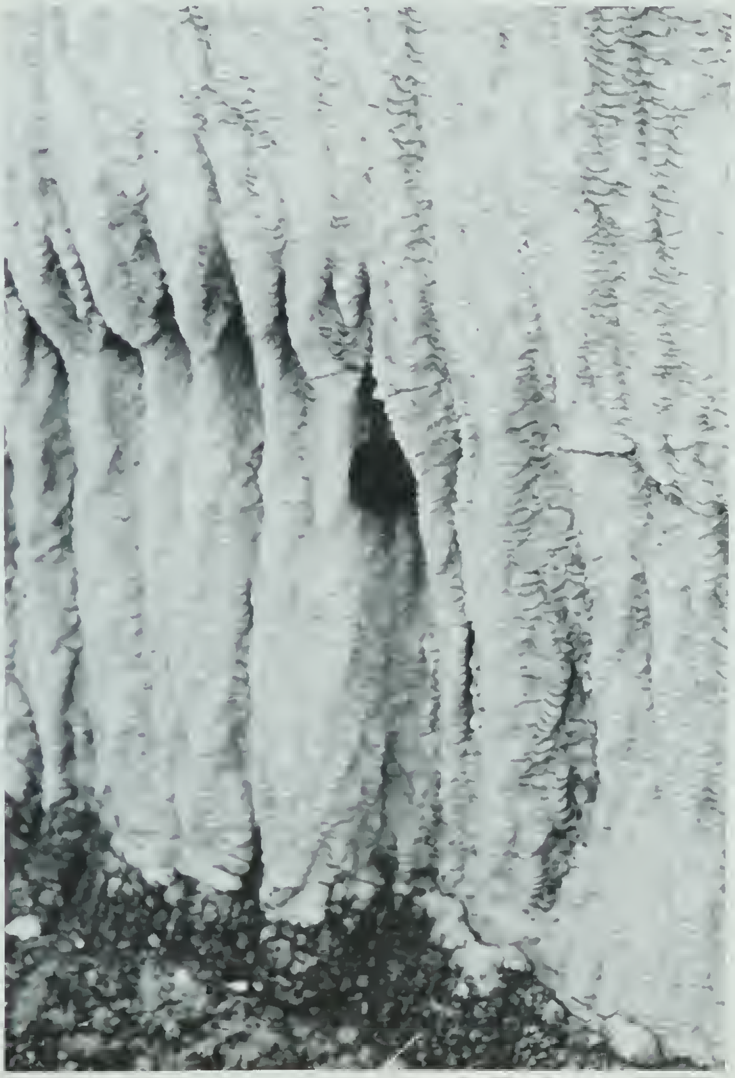


Plate 2. Curtain forms in the Tufa.

Plate 3. White Granular Precipitate beside Mound 1.

Plate 4. Conduits beneath Mound 1.

Plate 5. Vegetation Rim on Mound 3.

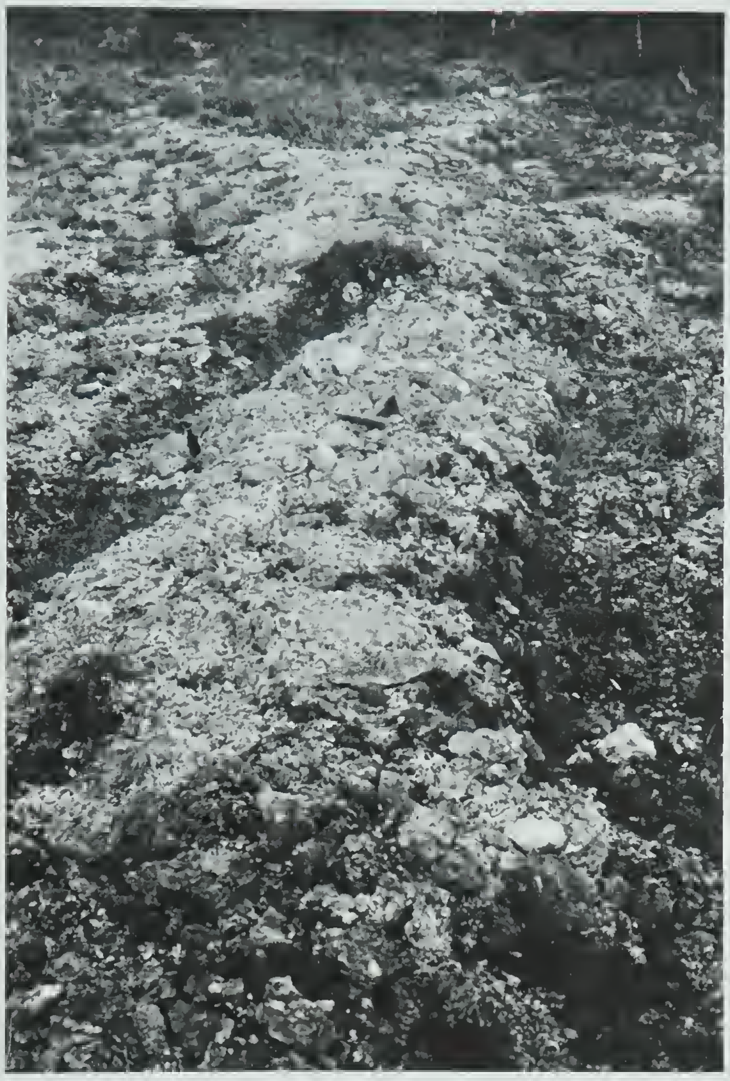


Plate 6. Patterned Ground Stripe in Tufa Area "a".

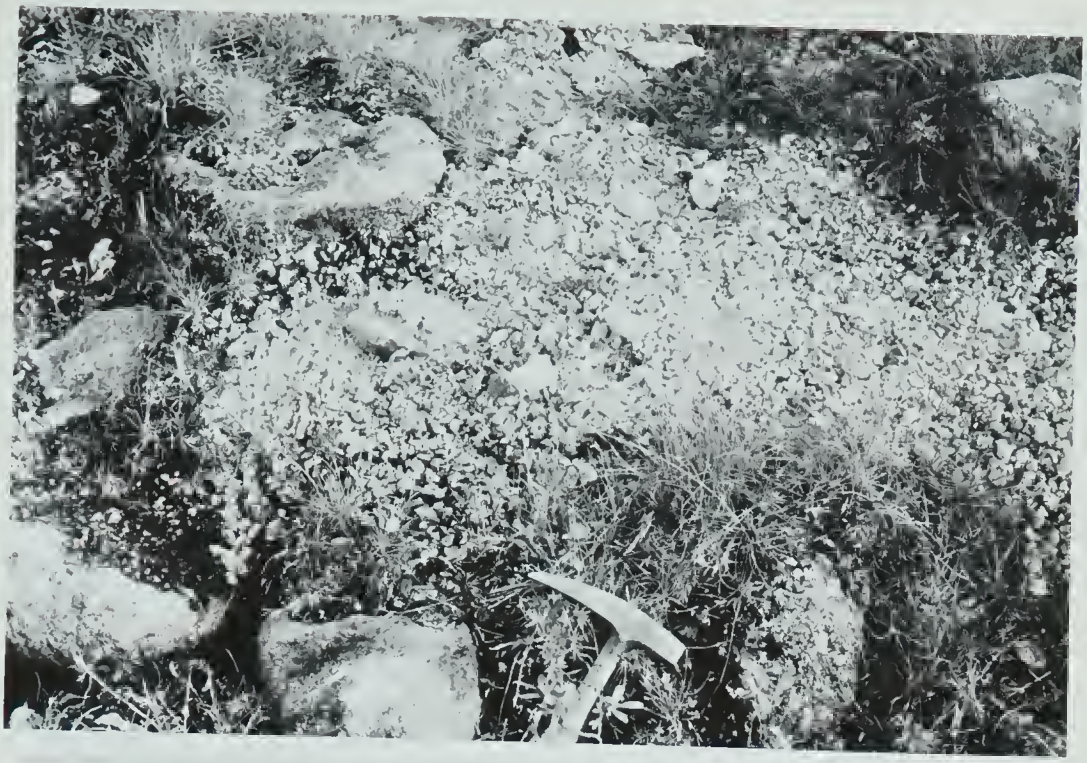


Plate 7. Equiforms in Tufa Area "b".

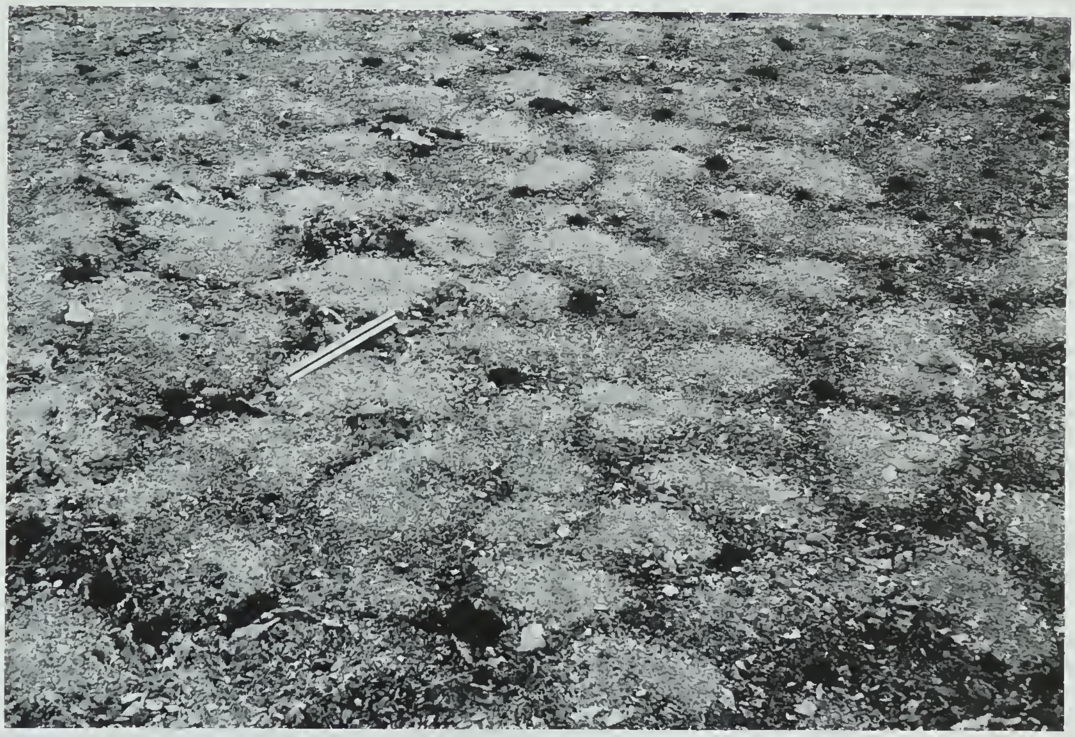


Plate 8. Equiforms on Mound 2.

Plate 9. Equiforms, east of Mound 2's Vent.

Plate 10. Exfoliation Structures on Mound 1.

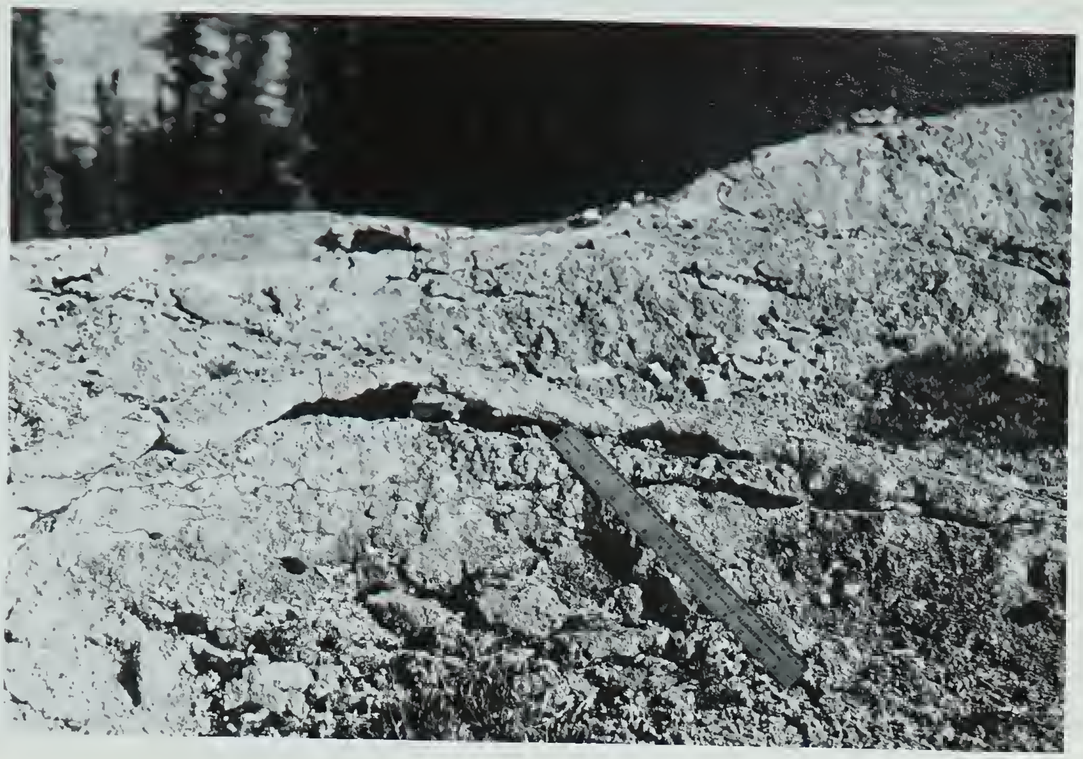


Plate 11. "A-tents" on Mound 1.

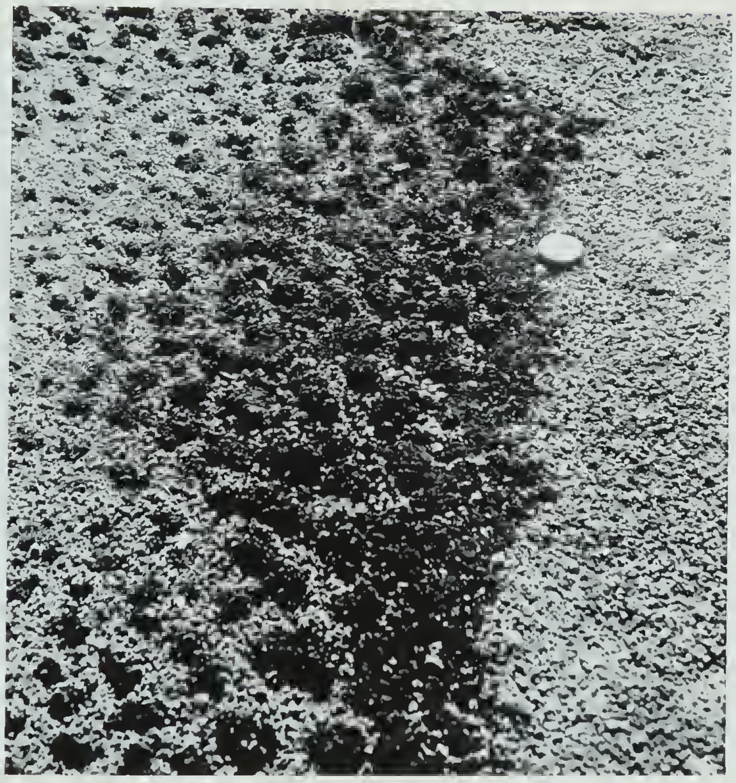


Plate 12. Frost Heave Structures.

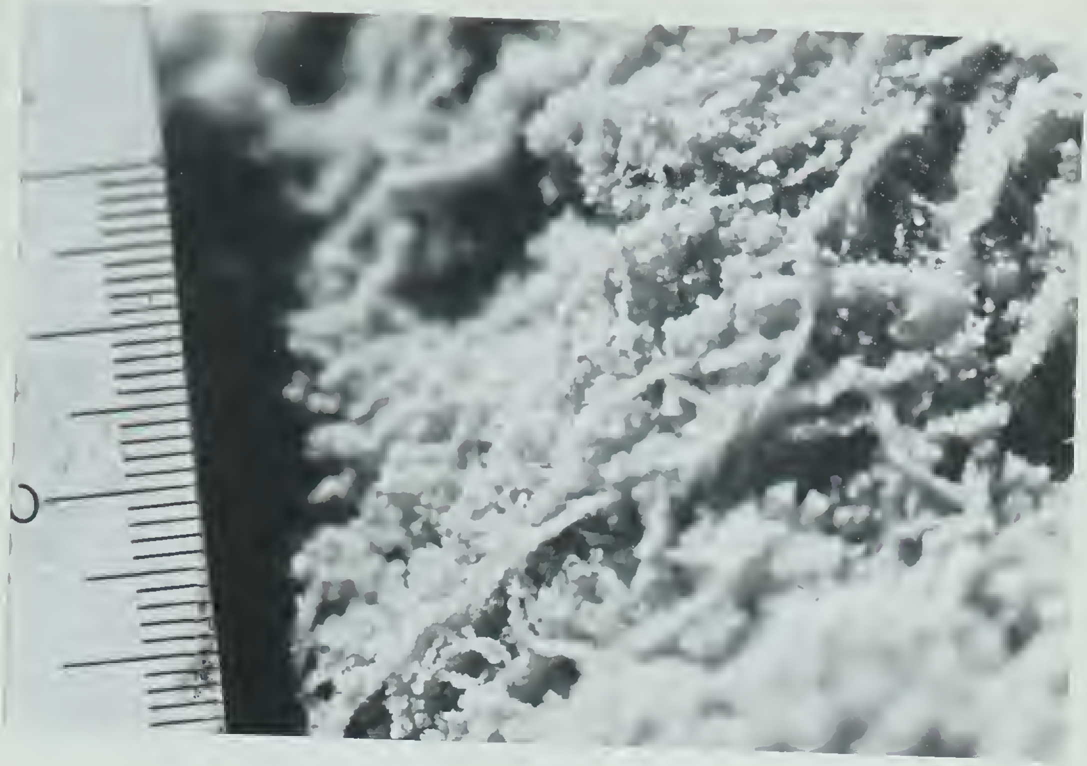


Plate 13. Calcified Algae Filaments.

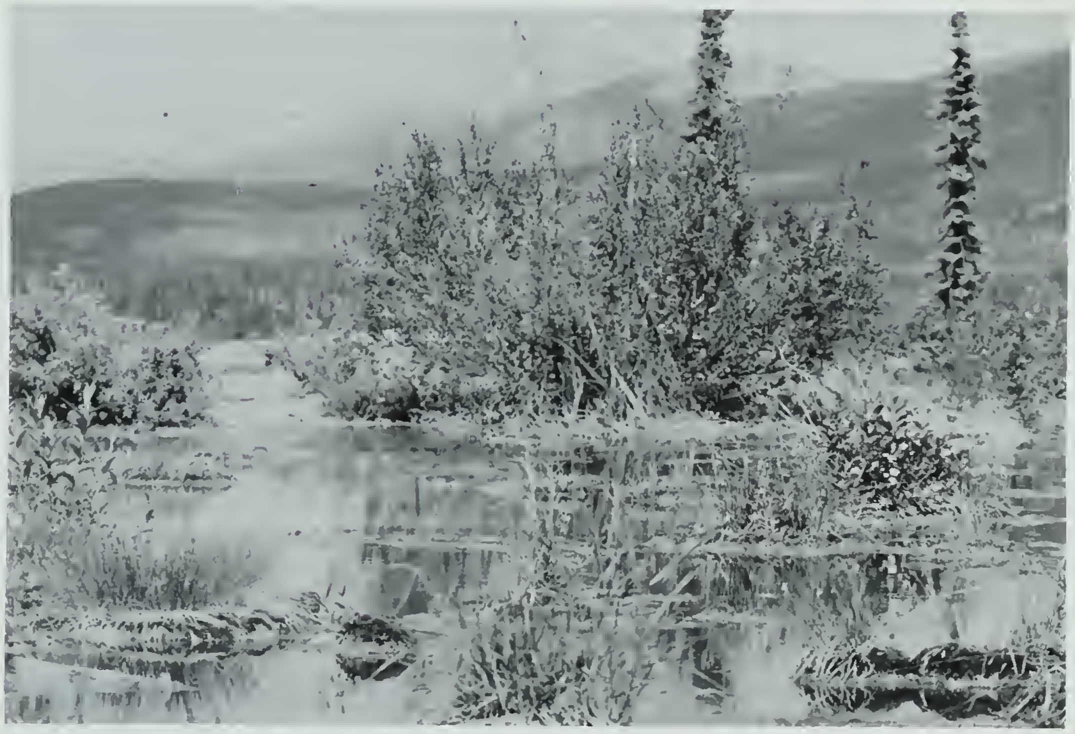


Plate 14. Vegetation Mounds on Mound 3.

Plate 15. Nippleoid Vegetation Mounds.

Plate 16. Vent 3. surrounded by *Juncus arcticus*.

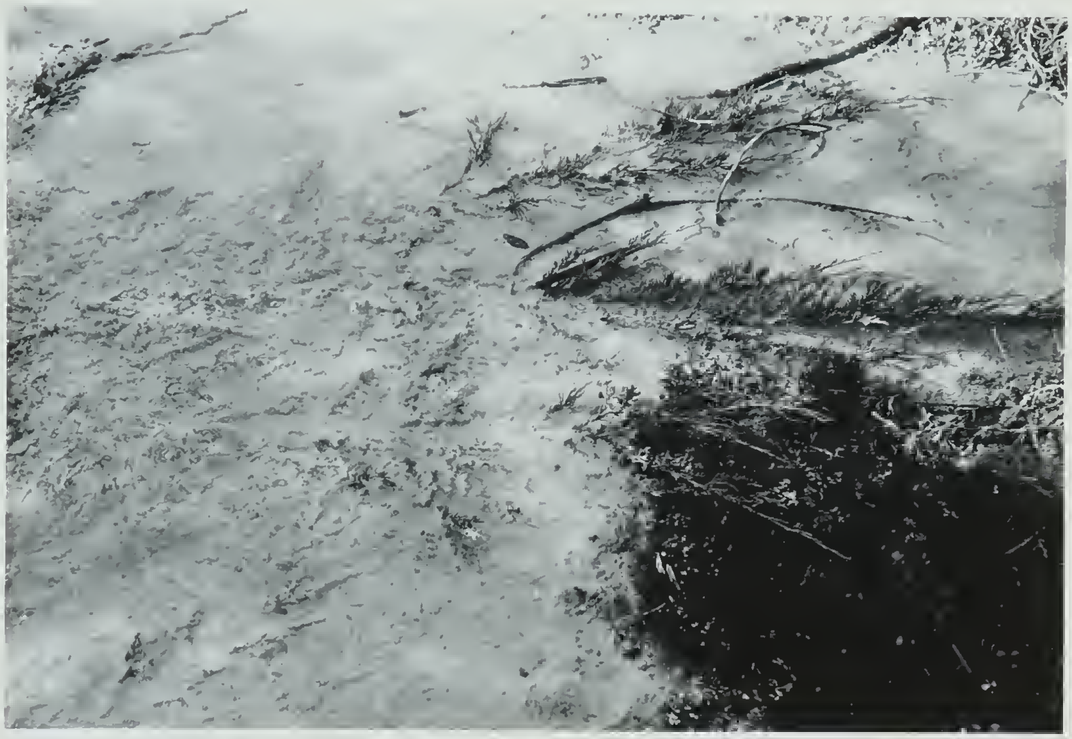


Plate 17. Calcification of *Juniperus horizontalis*.

APPENDIX 1

Relationship between slope of mound and rimstone pool width.

Slope (deg)	Pool width (cm)
1	12.7
25	0.79
2	10.16
41	0.63
<1	16.51
<1	22.86
0	38.1
4	5.39
1	10.16
1	9.37
14	0.95
1	15.24
5	0.52
1	15.24
2	12.7
28	0.79
19	0.96
14	1.11
37	0.64
39	0.32
25	0.79
41	0.48
41	0.64
1	10.48
6	0.64
1	1.59
2	8.26
4	3.81
3	2.86
<1	12.7
6	1.11
7	1.11
7	0.96
1	10.16
5	1.27
6	1.11
3	3.81
2	5.08
3	2.38
1	7.62
1	3.81
8	1.11
21	0.79
39	0.48
42	0.32
44	0.32
47	0.16
41	0.64
40	0.64
26	0.79
40	0.79
21	0.79
9	0.96
3	3.81
<1	12.7
1	10.16
32	0.79
22	0.79
39	0.64
40	0.48
5	1.59

APPENDIX 2

Relationship between rimstone pool width and height of rim.

Northern Sector

Top Section

pool width (metres)	rim height (metres)
1.89	0.27
1.74	0.12
0.24	0.06
1.37	0.18
1.10	0.09
2.96	0.40
1.80	0.37
3.84	0.52

Lower Section

pool width (metres)	rim height (metres)
2.11	1.86
0.92	1.28
0.73	0.49
0.49	0.55
0.82	0.55
0.02	0.015
0.02	0.82
0.82	0.52
0.55	0.95

Eastern Sector

Top Section

pool width (metres)	rim height (metres)
0.28	0.08
1.16	0.49
2.5	0.4
1.86	0.31
0.52	0.28
1.10	0.15

Lower Section

pool width (metres)	rim height (metres)
0.73	0.64
0.55	0.52
1.37	1.16
2.75	2.32
0.82	1.13
1.13	0.79
1.95	1.57
2.62	3.36
0.24	0.15

Southern Sector

Top Section

pool width (metres)	rim height (metres)
1.43	0.37
1.95	0.34
0.79	0.15
1.98	0.4
3.39	0.58
1.34	0.58
0.64	0.02

Lower Section

pool width (metres)	rim height (metres)
0.91	0.89
1.13	1.19
0.67	0.43
0.73	0.46
0.55	1.13
0.70	0.52
1.89	2.53
0.55	0.31
1.37	0.98

Western Sector*

pool width	rim height
0.67	0.98
0.31	0.55
0.64	0.03
0.98	0.18

* The western sector is active at present. There is no defined

boundary between top and lower section. Most of the pools have width of <0.06m with a rim height of 10^{-3}x3.05m This section is very fragile, hence few measurements were taken to avoid damage.

APPENDIX 3

Water hardness data

MOUND 1

Sample	Date	Air Temp °C	Water Temp °C	Total Hardness ppm	Ca ppm	Mg ppm
W1A	17.7.78	17.4	21.6	520	392	128
W1C	26.7.78	20.7	21.7	530	381	149
W1E	2.8.78	29	21.7	515	390	125
W1H	14.8.78	18.1	21.5	549	341	208
W1I	23.8.78	17.0	21.6	541	352	189

Two samples were taken at the base of mound 1 to determine how much calcium and magnesium is lost from solution.
Sample W1HX - taken from flow over edge of mound
Sample W1HY - taken from throughflow
Both were sampled at same time as sample W1H on 14 July 1978.

Sample	Total Hardness	Ca Hardness	Mg Hardness
W1HX	324 ppm	144 ppm	180 ppm
W1HY	322 ppm	142 ppm	180 ppm

MOUND 2

Sample	Date	Air Temp °C °C	Water Temp ppm	Total Hardness	Ca ppm	Mg ppm
W2A	17.7.78	17.4	20.7	482	394	88
W2C	26.7.78	20	20.7	480	390	90
W2E	2.8.78	29	21.5	520	395	125
W2G	7.8.78	21.5	20.7	513	388	125
W2H	14.8.78	16	20.8	548	381	167

MOUND 3

W3A	17.7.78	17.4	20.4	483	402	83
W3C	26.7.78	20.7	20.3	497	395	102
W3E	2.8.78	26.5	20.5	506	398	108
W3G	7.8.78	21.5	20.5	500	402	98
W3H	14.8.78	16	20.4	521	421	100

Samples W1B, W2B, W3B, W1D, W2D, W3d, W1F, W2F, W3F were in glass bottles which became contaminated

SPRING SHOWER

W4A	7.8.78	24	12.1	413	264	149
W4B	23.8.78	18	12.1	388	252	136

APPENDIX 4

Clast size in the patterned ground of tufa area "b".

(a)Large clasts in central section of the equiforms:

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	lithology
58	31	24	Granodiorite
67	46	28	"
58	43	28	"
40	40	24	"
67	28	29	Diorite
43	34	21	Granodiorite
46	34	18	"
40	34	28	Quartz Monzonite
43	31	28	"
62	46	30	Granodiorite
46	43	28	Quartz Monzonite
55	49	34	Granodiorite
55	43	31	"
52	34	24	"
49	37	24	"
43	40	27	Diorite
40	31	21	"
37	31	18	Tufa conglomerate
40	28	18	"
64	46	34	Granodiorite

Lithological percentages: Granodiorite - 60%; Quartz Monzonite - 15%; Diorite - 15%; Tufa conglomerate - 10%

(b) Middle section of aquiforms

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	Lithology
20	12	5	Granodiorite
18	12	6	"
9	6	5	Diorite
28	21	18	Granodiorite
21	18	12	Tufa conglomerate
4	4	3	Diorite
12	7	3	Diorite
12	7	3	Shale pyrite
9	6	3	"
9	7	5	Granodiorite
18	7	3	"
12	6	4	"
15	8	4	Shale pyrite
28	18	12	Granodiorite
24	16	9	"
9	4	3	Diorite

21	18	12	Granodiorite
15	12	9	Shale pyrite
18	9	4	Granodiorite
12	7	4	"

Lithological percentages: Granodiorite - 55%; diorite - 20%; shale pyrite - 20%; Tufa conglomerate - 5%.

(c) Outer section

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	Lithology
5.6	3.1	2.6	Tufa
4.7	4.1	1.4	"
4.5	3.1	4.2	"
2.2	2.1	1.2	"
1.8	1.3	0.6	"
2.0	1.3	0.7	Diorite
1.8	1.0	0.8	Shale Pyrite
1.7	1.1	0.5	"
1.6	1.3	1.3	Tufa
2.4	1.3	0.9	Shale Pyrite
1.8	1.3	0.5	Tufa
1.8	1.2	0.4	"
1.8	1.2	0.3	"

Smaller particles were measured by sieving and percentage weight calculated.

	Total	Particle size					
	weight	>4mm	2.83mm	2mm	1mm	10	<10
weight (gm)	168.6	154.2	5.72	2.85	2.54	1.12	1.65
% weight	100	91.5	3.4	1.8	1.6	0.7	1.0

APPENDIX 5

Clast size in patterned ground east of Mound 1

Large clasts

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	Lithology
40	31	28	Diorite
31	24	24	Tufa
18	18	6	Tufa conglomerate
15	12	12	Tufa
24	21	9	Tufa
18	15	8	"
28	15	15	Tufa conglomerate
46	34	34	Granodiorite
15	15	3	Tufa
49	46	43	Granodiorite
15	15	6	Tufa
70	40	34	Shale pyrite
49	34	28	Granodiorite
46	34	21	"
68	52	34	Shale pyrite
18	12	9	Tufa
40	31	21	Granodiorite
15	9	3	Tufa
18	12	3	Tufa
49	28	18	Granodiorite

Lithological percentages : Tufa - 45%; Granodiorite - 30%; Tufa conglomerate - 10%; Shale pyrite - 10%; diorite 5%.
No middle section could be defined in these equiforms.

Small clasts

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	"a" axis (cm)	"b" axis (cm)	"c" axis (cm)
3.5	2.9	2.1	2.3	2.0	0.9
3.0	3.0	1.1	2.3	1.8	1.1
4.6	2.9	1.6	2.1	1.6	1.6
4.2	2,9	1.9	2.7	1.4	1.0
3.1	2.9	1.4	2.4	2.1	1.6
3.5	2.4	1.4	2.0	1.9	0.5
2.8	1.8	1.6	2.1	2.0	1.5
3.2	1.6	1.5	2.5	1.9	1.4
2.8	2.1	1.8	3.1	1.8	1.0
1.9	1.9	1.1	2.6	1.3	1.0
1.8	1.7	1.4	1.4	1.2	1.0
2.1	1.5	0.8	1.3	1.2	0.4
1.5	1.3	0.5	1.3	1.0	0.6
1.9	1.3	0.7	1.4	1.2	0.3

1.5	1.4	0.9	1.1	1.0	0.5

lithology: 100% Tufa

APPENDIX 6

Clast size in patterned ground of tufa area "e".

Large clasts

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	Lithology
34	31	28	
55	40	37	Granodiorite
80	61	58	"
28	18	18	Tufa conglomerate
67	49	40	Diorite
49	43	28	Granodiorite
52	34	24	"
24	21	12	Tufa conglomerate
28	24	15	Quartzite
12	9	6	Tufa
37	28	24	Granodiorite
49	40	28	"
31	31	18	Quartzite
24	15	9	Diorite
9	6	6	Tufa
15	9	6	"
12	6	6	"
24	18	9	Diorite
49	31	28	Tufa Conglomerate
31	28	18	Quartzite

Lithological percentages: Granodiorite - 35%; Tufa - 20%; Tufa conglomerate - 15%; Diorite - 15%; Quartzite - 15%.
No clearly defined middle section

Fine material

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	Lithology
7.1	4.3	2.3	Diorite
3.8	3.7	2.4	Granodiorite
5.7	2.6	0.5	tuff?
2.2	1.9	1.0	Tufa
2.8	1.7	1.3	"
2.9	2.1	1.2	"
1.9	1.8	1.6	"
1.8	1.6	0.8	"
1.9	1.2	1.0	"
1.4	1.2	1.0	"
1.2	0.9	0.5	"
1.9	1.7	1.5	"
2.2	1.6	1.2	"
1.5	1.2	1.1	"
1.5	1.3	1.2	"

1.8	1.1	0.9	"
2.2	1.6	0.6	"
1.8	1.3	1.2	"
2.1	1.3	0.8	"
1.5	1.3	1.1	"
1.4	1.1	1.0	"
1.6	1.5	1.0	"
1.3	1.0	1.0	"
1.1	1.1	0.8	"

Lithological percentage: >85% Tufa.

Size of the very fine material was calculated as a percentage weight.

	Total		Particle Size*				
	weight	>4mm	2.83mm	2mm	1mm	10	<10
Weight (gm)	246.6	225.8	3.9	2.9	4.9	2.7	6
% weight	100	91.5	1.6	1.2	2	1.1	2.4

*Particle size was determined by sieving using sieves with the above mesh size.

APPENDIX 7

Clast size of equiforms adjacent to vent 2

Large clasts (Sample PG3) from equiform edge

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)	"a" axis (cm)	"b" axis (cm)	"c" axis (cm)
6.9	5.7	2.3	5.0	4.2	1.5
4.7	4.0	1.5	4.6	2.3	2.0
5.1	1.9	1.2	4.7	2.5	1.8
3.8	1.9	1.3	2.8	2.1	1.4
3.5	2.5	1.7	3.6	1.2	1.6
2.6	1.5	1.0	2.8	1.7	0.8
2.2	2.0	0.9	2.5	1.9	1.1
2.0	1.7	0.8	2.4	1.9	1.0
3.3	1.2	1.0	2.5	1.6	0.7
2.4	1.6	0.9	2.6	1.3	1.2
2.0	1.3	0.5	2.4	1.6	0.8
2.6	1.4	0.6	2.2	1.2	0.8
2.0	0.9	0.9	1.8	1.2	0.7
1.7	1.3	0.8	1.8	1.4	0.4
5.0	3.6	1.5	3.3	1.8	0.4
3.8	3.2	2.1	1.9	1.7	1.2
3.9	2.4	1.4	2.5	1.7	0.5
3.3	1.8	1.2	2.1	1.3	0.9
2.6	1.6	1.1	2.3	1.3	0.7
2.6	2.0	1.1	1.7	1.6	0.9
2.6	2.0	0.9	2.1	1.2	0.5

All particles are tufa.

Intermediate sized clasts (Sample PG2) from middle of equiform radius.

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)
3.2	2.5	0.9
2.0	1.9	0.8
1.8	1.1	0.6
1.7	1.3	0.7
2.2	1.6	0.8
1.8	1.3	1.1
1.6	1.1	0.5
1.3	1.0	0.7
2.2	1.4	0.6
2.4	1.0	0.6
1.8	1.3	0.5

Smaller particle size in sample PG2 was calculated as a percentage weight by sieving:

	Total		Particle size				
	weight	>4mm*	2.83mm	2.0mm	1.00mm	1φ	<1φ
Weight (g)	115.88	44.23	23.4	22.63	21.01	3.48	1.13
% weight	100	38	20	19.5	18.1	3	0.9

*Size Listed above

Size of small particles from centre of equiform (Sample PG1) was calculated as a percentage weight by sieving:

	Total		Particle size				
	weight	>4mm	2.83mm	2mm	1mm	1φ	<1φ
Weight (g)	76.22	3.7	10.4	30.95	14.04	8.84	8.29
% weight	100	4.9	13.65	40.61	18.43	11.6	10.88

APPENDIX 8

Patterned ground of stripe form adjacent to vent 2

Large clasts (Sample PG9) along margins of stripes

"a" axis (cm)	"b" axis (cm)	"c" axis (cm)
7.6	2.3	1.9
7.6	3.9	2.0
2.3	1.6	0.4
1.9	1.7	1.4
1.6	1.3	0.5
2.5	1.0	0.5
1.8	1.3	0.4
1.9	1.1	0.4
1.2	1.1	0.4
1.6	1.3	0.9
1.6	1.0	0.3
1.3	1.0	0.6

Lithology - 100% tufa

Size of smaller particles along the margins was calculated as a percentage weight by sieving:

	Total	Particle size					
	weight	>4mm	2.83mm	2mm	1mm	10	<10
Weight(g)	143.97	120.68	20.14	1.89	0.15	0.12	0.99
% weight	100	83.8	14	1.3	0.1	0.1	0.63

Size of smaller particles along median of stripes was calculated as a percentage weight by sieving:

	Total	Particle size					
	weight	>4mm	2.83mm	2mm	1mm	10	<10
Weight(g)	49.2	11.95	24.66	11.2	1.1	0.07	0.23
% weight	100	24.3	50	23	2.2	0.14	0.46

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